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New Technology for Remote Testing of Response Time of Installed Thermocouples

Volume II — Research Data

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13. ABSTRACT (Maximum 200 words)

A comprehensive research and development project was completed to provide new technology for remote testing of response time of thermocouples as installed in operating processes.

A significant portion of this development depended on the Loop Current Step Response (LCSR) method. This method is based on heating the thermocouple internally by applying an electric current to its extension leads. The current produces Joule heating in the thermocouple and causes the thermocouple junction to settle several degrees above the ambient temperature. The current is then cut off and the thermocouple output is recorded as it cools to the ambient temperature. It has been established by experimental research and theoretical development carried out in this project that this cooling transient can be analyzed to provide the response time of the thermocouple under the conditions tested.

With little additional effort, the equipment that was developed in this project can be adapted to provide a capability for in-situ assessment of static health, reliability, and accuracy of installed thermocouples.

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PREFACE

This is Volume II of a three volume report written on a research and development project conducted by Analysis and Measurement Services Corporation (AMS) for Arnold Engineering Development Center (AEDC). The purpose of this project was to develop equipment and procedures for in-situ response time testing of thermocouples using the Loop Current Step Response (LCSR) method. The principle of the LCSR method for response time testing of thermocouples is covered in Volume I. This volume (Volume II) is devoted to the research data in support of the LCSR test. It also provides the details of the experiments conducted to establish the validity and the accuracy of the LCSR method. The LCSR test equipment that was developed in this project is described in Volume III under a separate cover.

This Volume II report contains four appendices. The most important of these is Appendix C with the details of a survey of the aerospace community for the applications of the LCSR method.

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1. INTRODUCTION

This is Volume 2 of a three volume report on a research and development project successfully completed to develop equipment and procedures for measurement of the response time of thermocouples as installed in aerospace processes. This volume provides samples of the raw data and analysis results obtained during the research portion of Phase II of the two phase project.

The development documented herein was based on the Loop Current Step Response (LCSR) technique as described in Volumes 1 and 3 of this report. The data and results presented in this volume cover research conducted in the following areas:

1. Laboratory validation of the LCSR method in water.
2. Laboratory validation of the LCSR method in air.
3. Effects of fluid flow rate on response time of thermocouples in water.
4. Effects of fluid flow rate on response time of thermocouples in air.
5. Determination of optimum electrical current and heating times for response time testing of thermocouples using the LCSR technique.
6. Effects of various extension wire lengths on LCSR signals for thermocouples in water.
7. Effects of various extension wire lengths on LCSR signals for thermocouples in air.
8. Thermocouple Calibration

   A. Thermocouple calibration repeatability.
   B. Effects of LCSR testing on thermocouple calibration.
   C. High temperature calibration of thermocouples.

In addition, supplemental testing was performed to provide additional insight into thermocouple characteristics. Some examples are:

1. LCSR testing for transient temperature measurement inside nozzle materials used in solid fuel rocket engines.

2. LCSR testing for thermocouples installed in supersonic wind tunnels.

3. LCSR testing for thermocouples installed in subsonic wind tunnels.

4. Determination of inhomogeneities in typical thermocouples.

5. Application of noise analysis techniques for response time testing of thermocouples.

6. Determination of temperature increases in thermocouple extension wire during LCSR testing.

7. Repeatability of LCSR results.

8. Dynamic heat transfer modeling of thermocouples.

The majority of research reported herein was conducted on typical type "E", "J", "K", and "T" thermocouples of various sizes. These thermocouples were specified by the Air Force as the types that are of interest to Arnold Engineering Development Center (AEDC). The type "J" and type "K" thermocouples were specified as those of primary interest, and type "E" and type "T" were specified as thermocouples of secondary interest. A full listing of the thermocouples used in the project is provided in Appendix A. Appendix B provides the source code for a thermocouple modeling program developed during this project which is described in detail in Section 11. Appendix C is a copy of a report which was generated to verify that a need for thermocouple LCSR exists for aerospace applications.

It should be pointed out that the terms flow rate, flow, fluid flow, fluid flow rate, and flow velocity are used in this report interchangeably to refer to the velocity of liquids and gases that were involved in the experiments that we conducted during the project. Furthermore, the words time constant, response time, and time response are used in this report interchangeably. The use of the word time constant in expressing the speed of response of a thermocouple is not intended to imply that the thermocouple is necessarily a first order system.

2. BASELINE TESTS

The thermocouples selected for the project were first tested using the conventional plunge test technique to identify their time constants in water and air at reference flow rates. A listing of the thermocouples tested is given in Table 2.1. The time constant results for reference conditions in water and air are given in Tables 2.2 and 2.3. These results were used for validation of the LCSR technique as discussed later in this report. Basically, the validation involved comparing the plunge test results with the LCSR results to determine the validity and accuracy of the LCSR method for providing the time constants of thermocouples.

Typical plunge test transients obtained from actual laboratory tests are provided for each of the following cases:

1. An ideal plunge test transient (Figure 2.1). This data represents a step trigger signal and the corresponding thermocouple output transient. The plunge test was performed by heating the thermocouple in air using a warm air blower and plunging it into the test environment (room temperature water). The trigger signal, in this case channel one of the recording, identifies the beginning of the test. The plunge test setup, shown in Figure 2.2, consisted of the test media (water bath or air loop), amplifier, multimeter, reference block, and strip chart recorder.

2. Typical plunge test transients for a thermocouple in water and in air (Figures 2.3 and 2.4). These figures are intended to illustrate that the response is strongly dependant on the condition which the thermocouple is operated. Figures 2.3 and 2.4 are for a type "E" thermocouple. Similar data are shown in Figures 2.5 through 2.10 for type "J", "K", and "T" thermocouples. Note that the changes in transient slope (present on some of the recordings) is due to slowing of strip chart recorder speed, and not indicative of changes in thermocouple response.

3. Typical plunge test transients for thermocouples exposed to high subsonic air flow rates. (Figures 2.11 and 2.12).

TABLE 2.1

Thermocouple Plunge Test Listing

Item #	Tag #	Type	O.D. (mm)
1	AF#03	K	6
2	AF#04	K	6
3	AF#07	K	5
4	AF#09	K	3
5	AF#13	K	2
6	AF#14	K	6
7	AF#15	K	6
8	AF#16	K	6
9	AF#18	K	wire
10	AF#20	K	wire
11	AF#22	K	wire
12	AF#23	K	wire
13	AF#49	K	2
14	AF#50	K	2
15	AF#27	E	5
16	AF#29	E	3
17	AF#43	E	2
18	AF#44	E	6
19	AF#45	E	2
20	AF#51	E	2
21	AF#36	J	5
22	AF#38	J	3
23	AF#40	J	2
24	AF#46	J	6
25	AF#47	J	2
26	AF#48	J	2
27	AF#52	J	2

TABLE 2.2

Time Constants in Various Water Flow Rates
(all times are in seconds)

		Flow Rate			
Tag #	Diam/Type	0.2 m/s	0.3 m/sec	0.6 m/s	1 m/sec
AF# 03	6mm K	1.66	1.39	1.27	1.15
AF# 04	6mm K	3.40	3.12	3.06	2.74
AF# 07	5mm K	3.33	2.88	2.72	2.69
AF# 09	3mm K	0.91	0.80	0.76	0.74
AF# 13	2mm K	0.37	0.29	0.27	0.26
AF# 27	5mm E	2.75	2.10	2.00	1.91
AF# 29	3mm E	1.76	1.51	1.40	1.38
AF# 36	5mm J	2.04	1.72	1.43	1.36
AF# 38	3mm J	2.20	2.00	1.90	1.76
AF# 40	2mm J	0.51	0.42	0.43	0.42
AF# 43	2mm E	0.47	0.38	0.37	0.34
AF# 44	6mm E	3.02	2.21	2.10	1.87
AF# 45	2mm E	0.35	0.24	0.24	0.21
AF# 46	6mm J	3.07	2.22	1.98	1.84
AF# 47	2mm J	0.44	0.35	0.33	0.32
AF# 48	2mm J	0.29	0.20	0.19	0.18
AF# 49	2mm K	0.29	0.21	0.19	0.17
AF# 50	2mm K	0.39	0.30	0.29	0.27

TABLE 2.3

Thermocouple Plunge Results in Air
(all times are in seconds)

TC Tag #	O.D./Type	Flow Rate 4.5 m/s	9 m/s	14 m/s	18 m/s
AF# 4	6mm K	53.50	35.70	26.15	23.40
AF# 44	6mm E	45.25	33.00	23.90	22.00
AF# 46	6mm J	51.65	33.90	24.85	22.70
AF# 7	5mm K	35.00	23.95	17.13	15.95
AF# 27	5mm E	34.45	24.15	17.10	15.45
AF# 36	5mm J	34.75	23.00	17.50	15.30
AF# 9	3mm K	18.43	13.35	10.03	8.59
AF# 29	3mm E	21.90	14.39	10.55	9.10
AF# 38	3mm J	19.20	13.14	9.90	9.25
AF# 13	2mm K	7.15	4.71	3.66	3.37
AF# 40	2mm J	5.43	4.13	3.20	2.96
AF# 43	2mm E	8.20	5.26	3.88	3.53
AF# 51	2mm exp E	3.64	1.94	1.12	0.98
AF# 52	2mm exp J	4.03	2.03	1.28	1.13
AF# 18	wire K	1.21	0.36	0.14	0.14
AF# 20	wire K	0.46	0.24	0.16	0.15
AF# 22	wire K	1.67	0.71	0.49	0.43
AF# 23	wire K	1.18	0.71	0.50	0.44
AF# 14	6mm flex K			2.20	1.60
AF# 15	6mm flex K			1.20	0.60
AF# 16	6mm flex K			2.70	1.90

Subsonic Wind Tunnel Data

TC Tag #	O.D./Type	27 m/sec	45 m/sec	54 m/s
AF# 14	6mm K	1.40	1.20	
AF# 15	6mm K	0.70	0.40	
AF# 16	6mm K	1.70	1.10	
AF# 40	2mm J	2.45	2.22	
AF# 18	wire K	0.08	0.08	
AF# 22	wire K	0.40	0.27	
AF# 29	3mm E	8.00		6.00

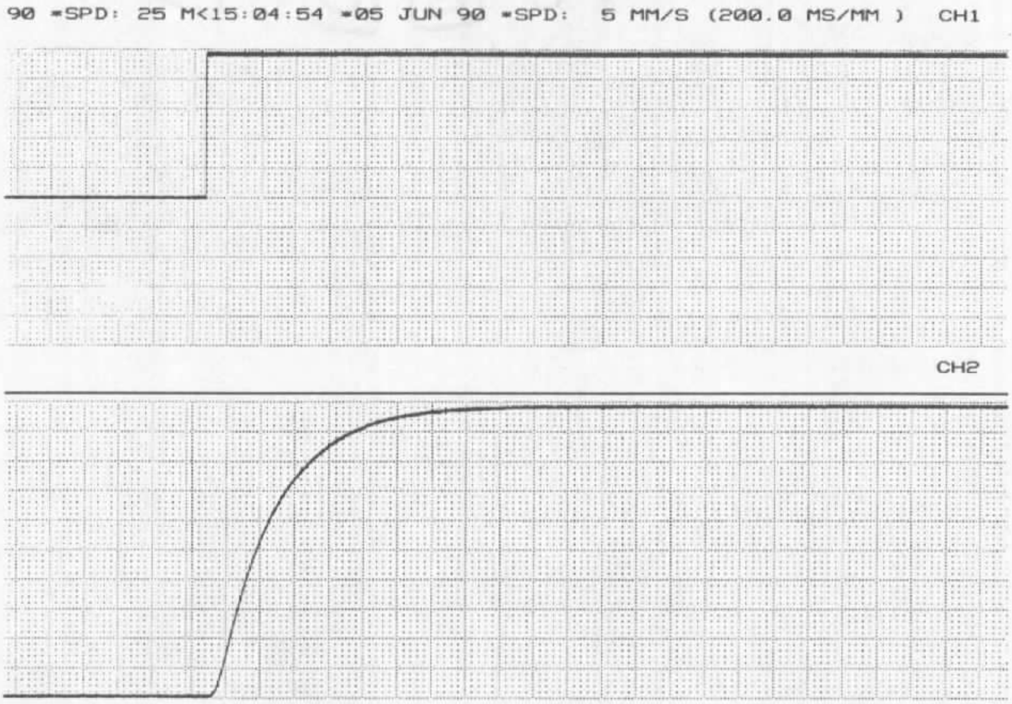
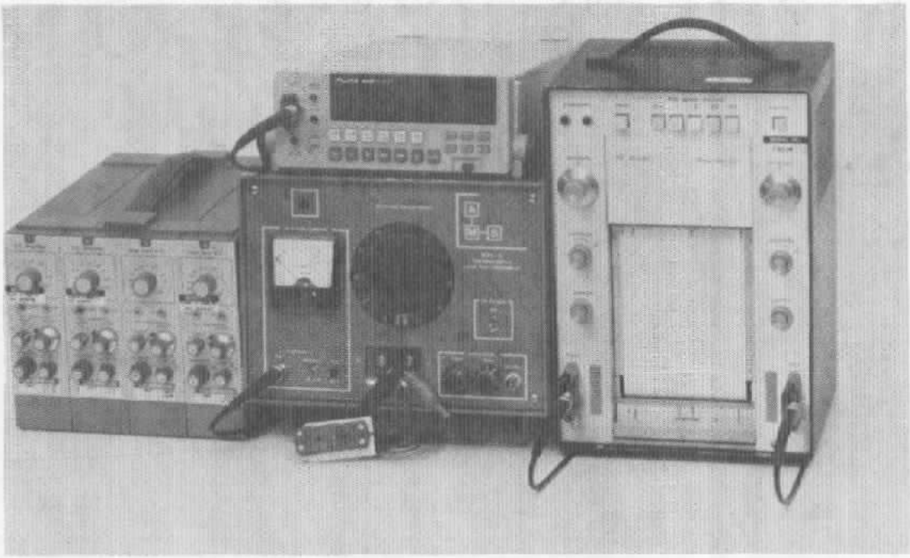


Figure 2.1. Typical Thermocouple Plunge Response (CH1-Trigger, CH2-Thermocouple Response).



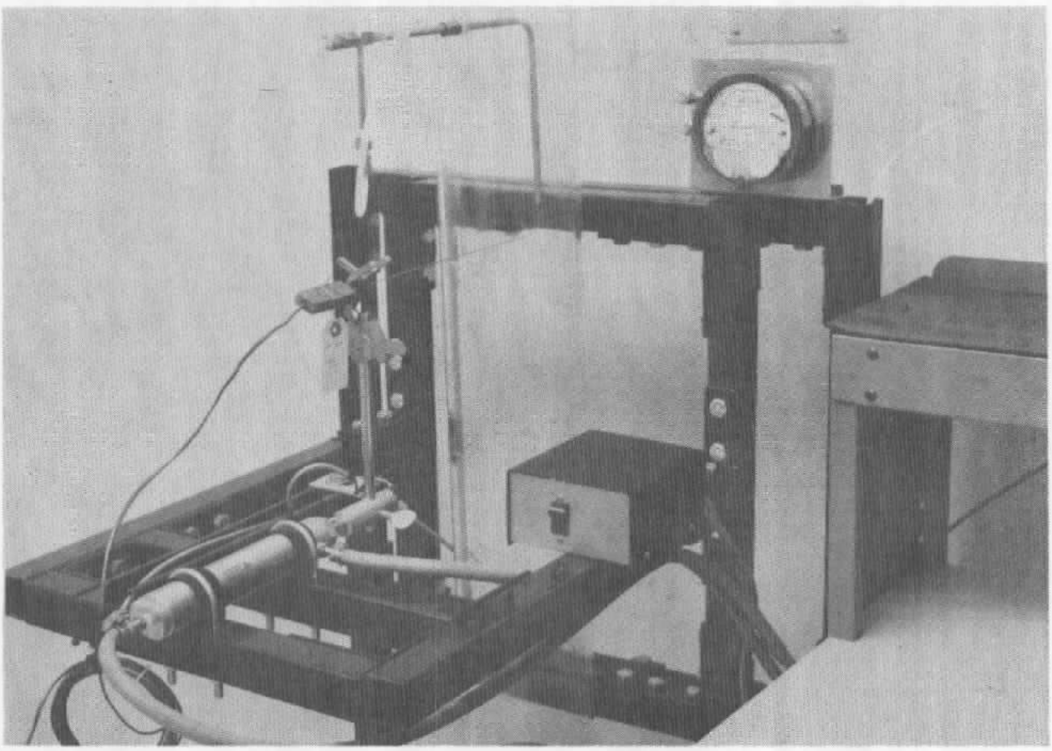


Figure 2.2. Plunge Test Setup.

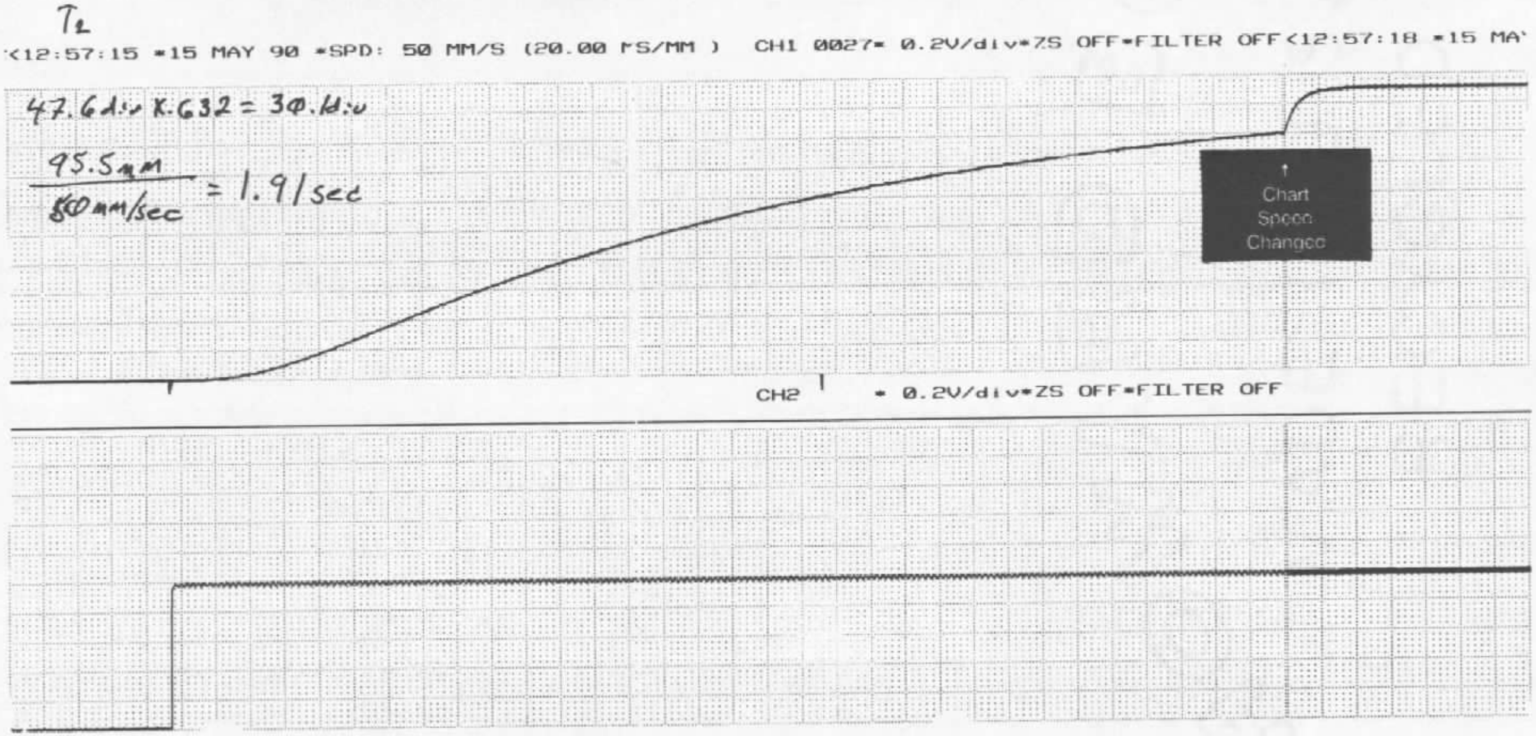


Figure 2.3. Typical Plunge Response for Type "E" Thermocouple in Water.

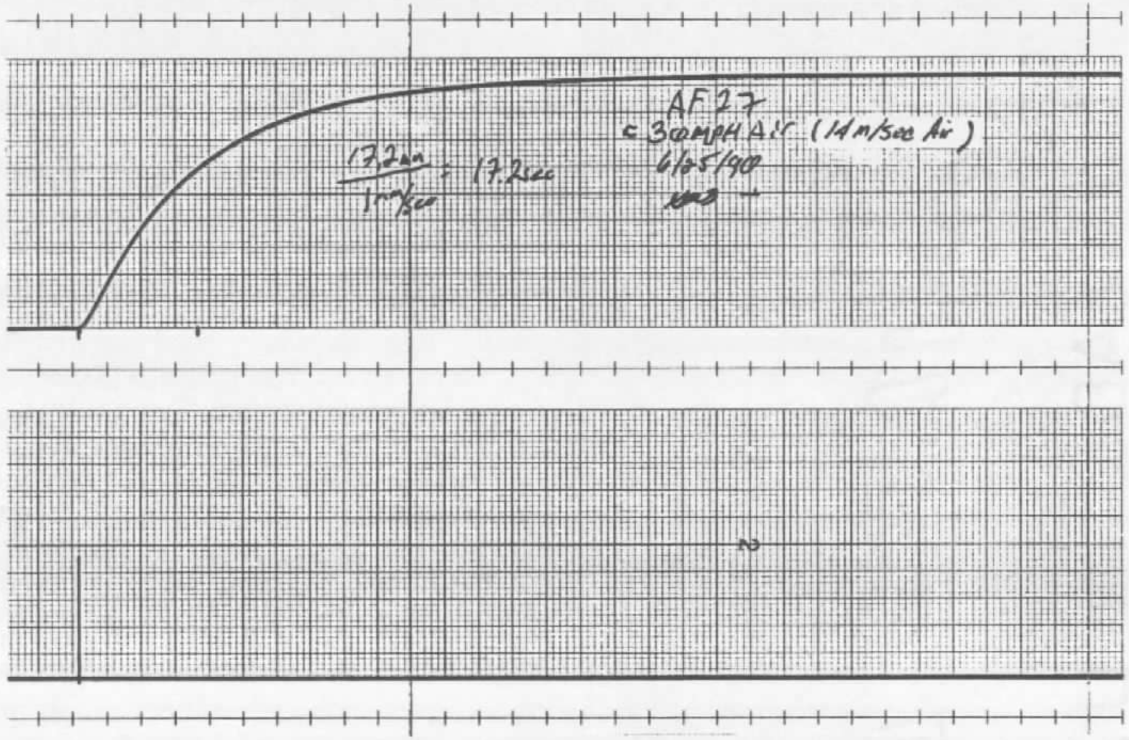


Figure 2.4. Typical Plunge Response for Type "E" Thermocouple in Air.

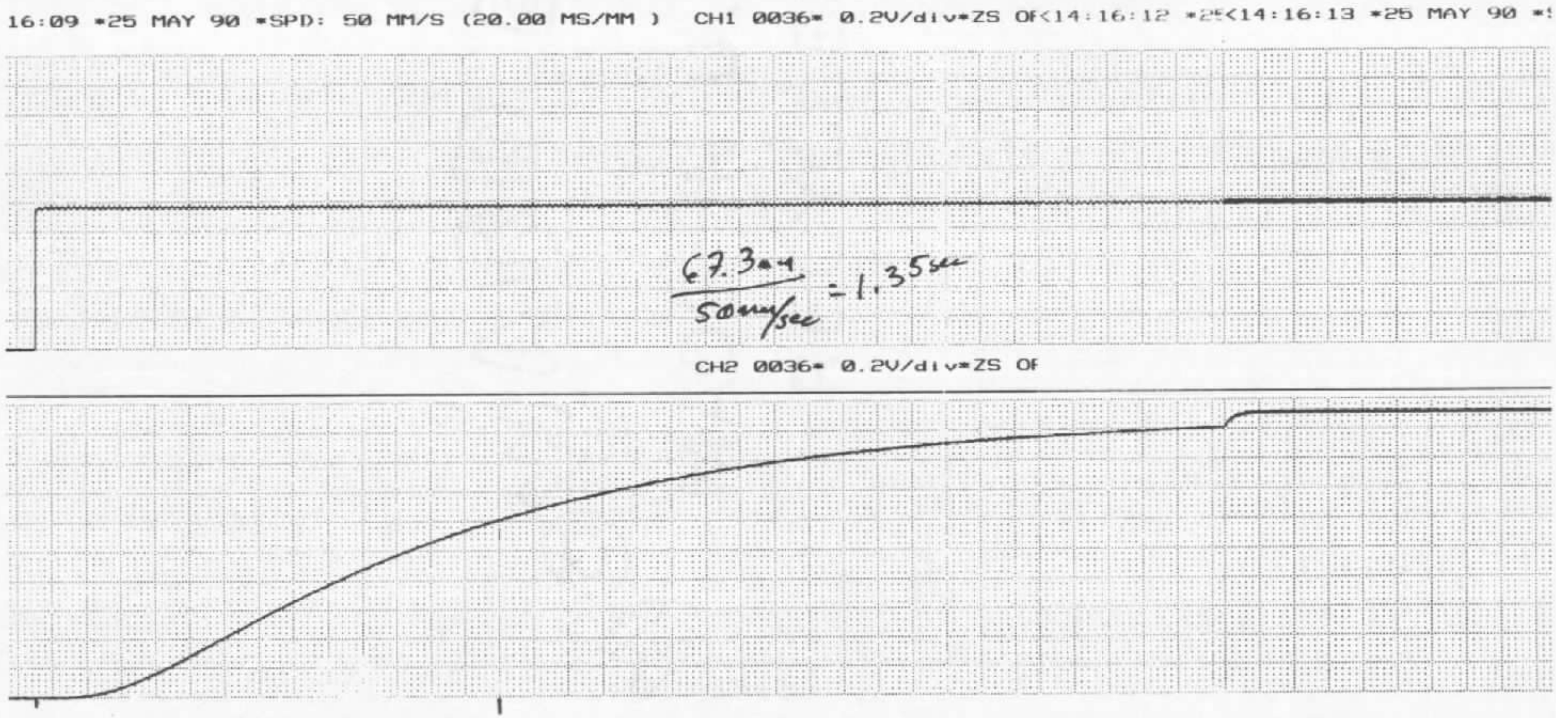


Figure 2.5. Typical Plunge Response for Type "J" Thermocouple in Water.

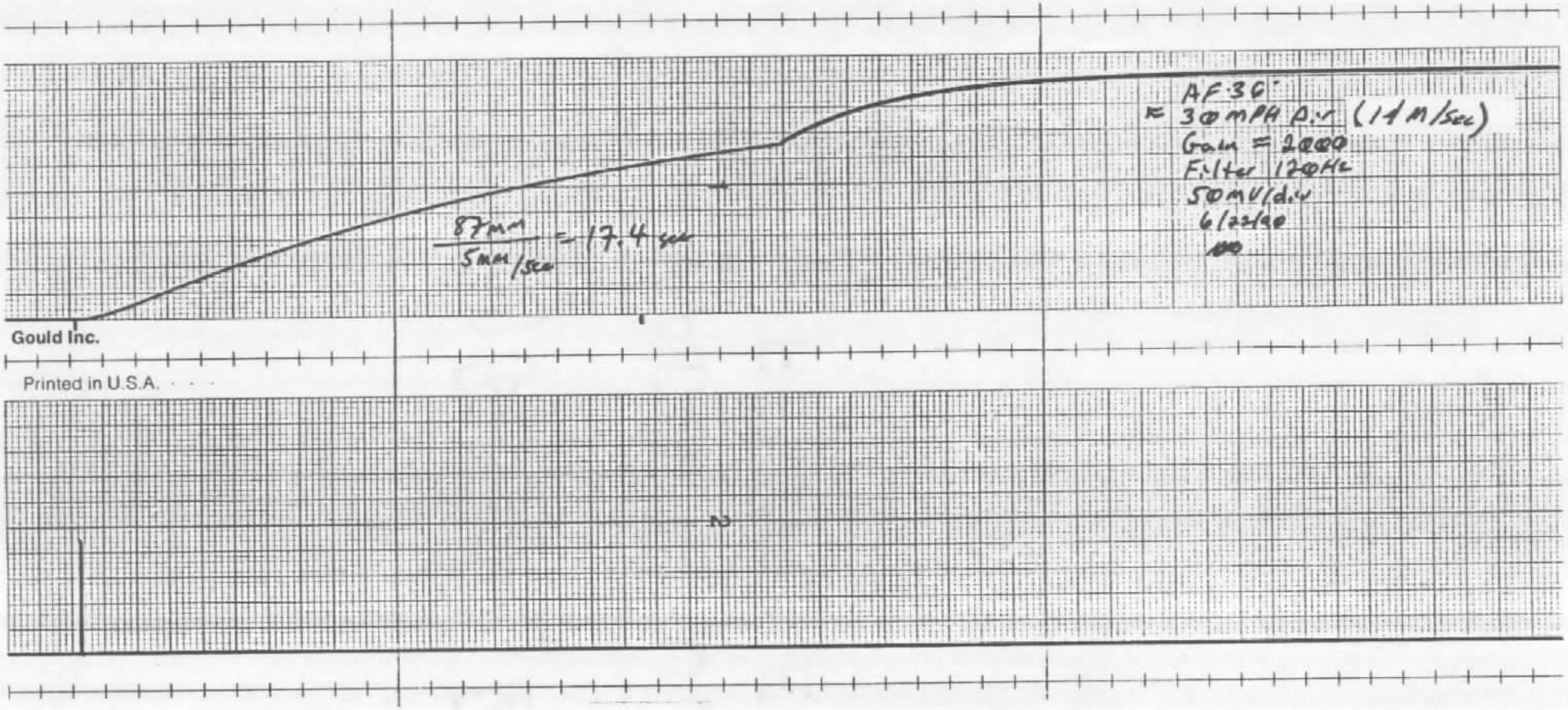


Figure 2.6. Typical Plunge Response for Type "J" Thermocouple in Air.

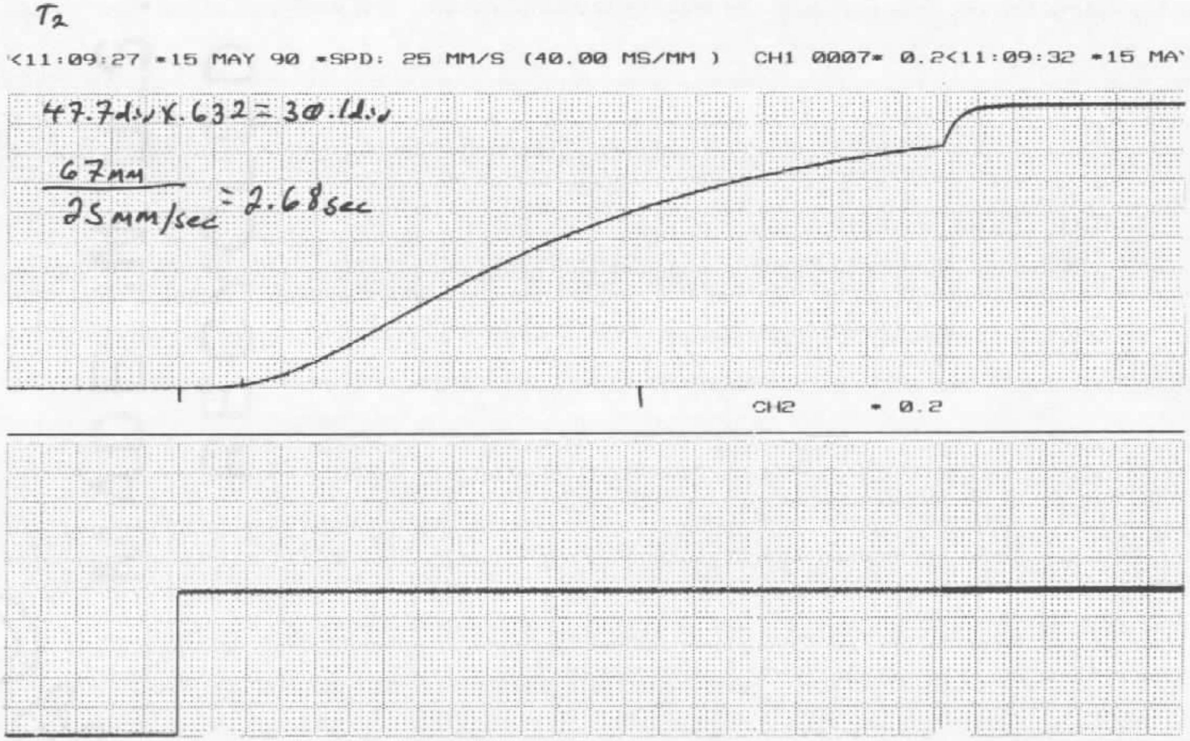


Figure 2.7. Typical Plunge Response for Type "K" Thermocouple in Water.

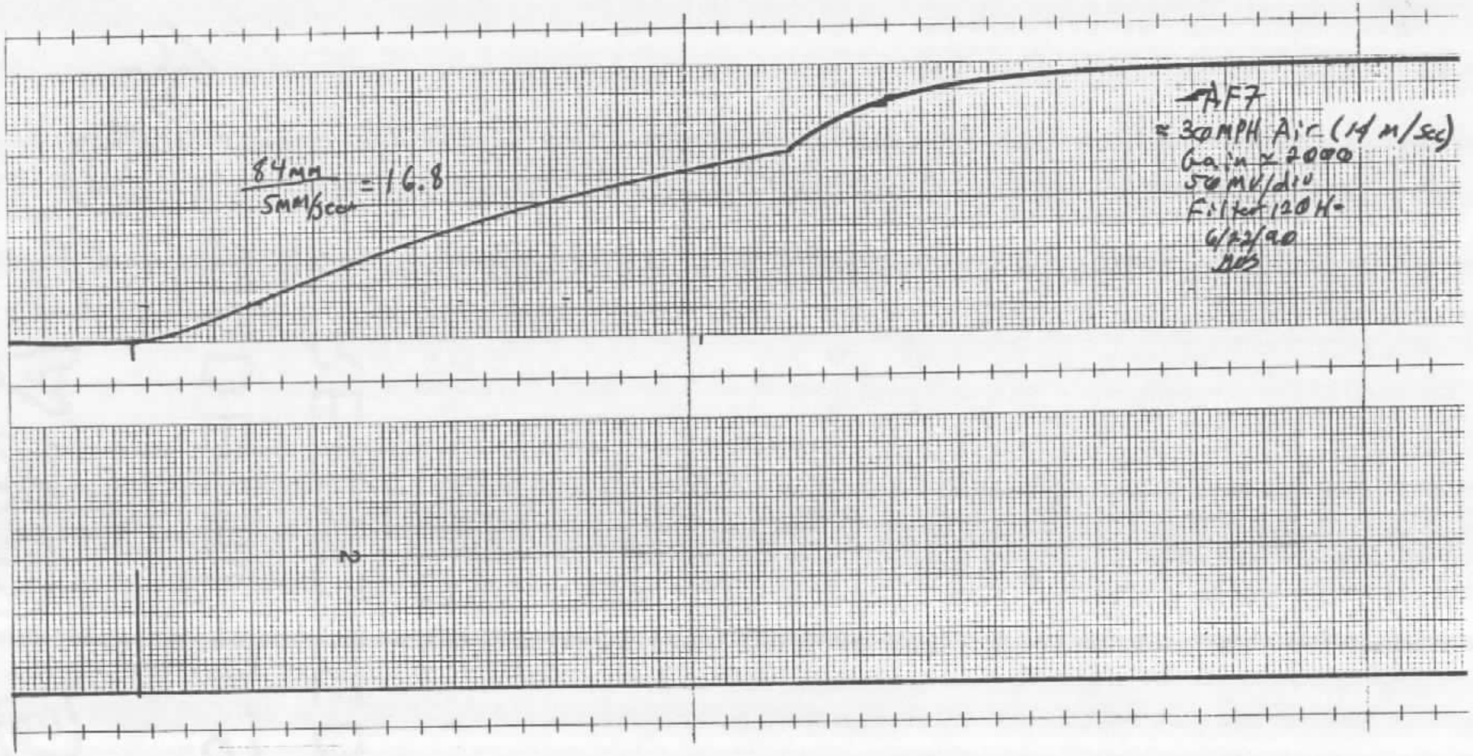


Figure 2.8. Typical Plunge Response for Type "K" Thermocouple in Air.

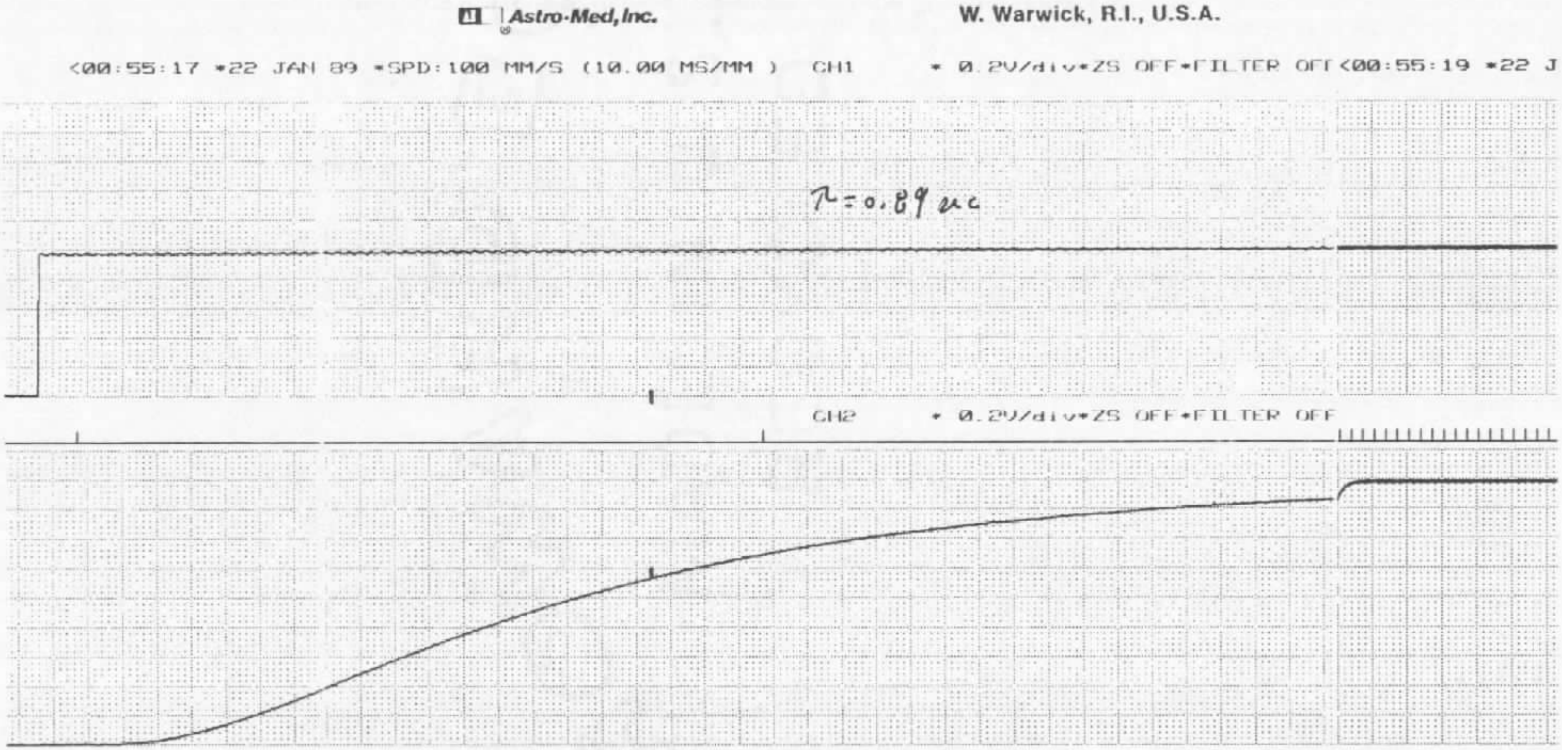


Figure 2.9. Typical Plunge Response for Type "T" Thermocouple in Water.

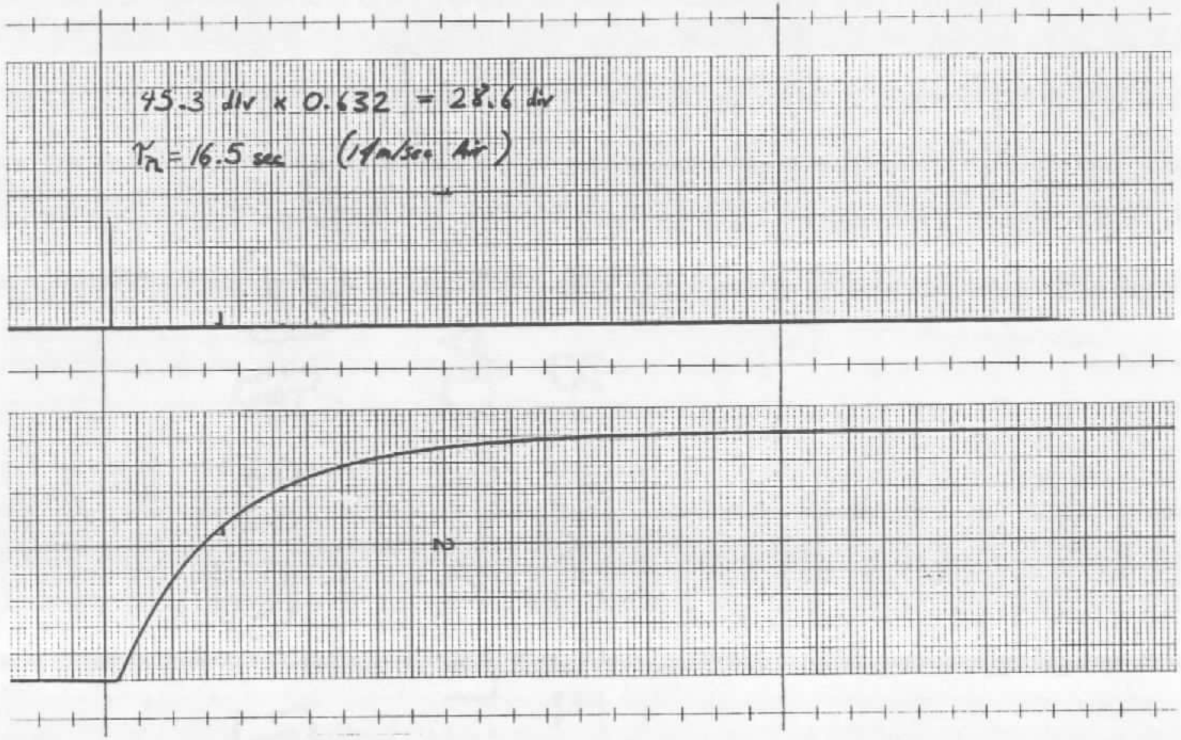


Figure 2.10. Typical Plunge Response for Type "T" Thermocouple in Air.

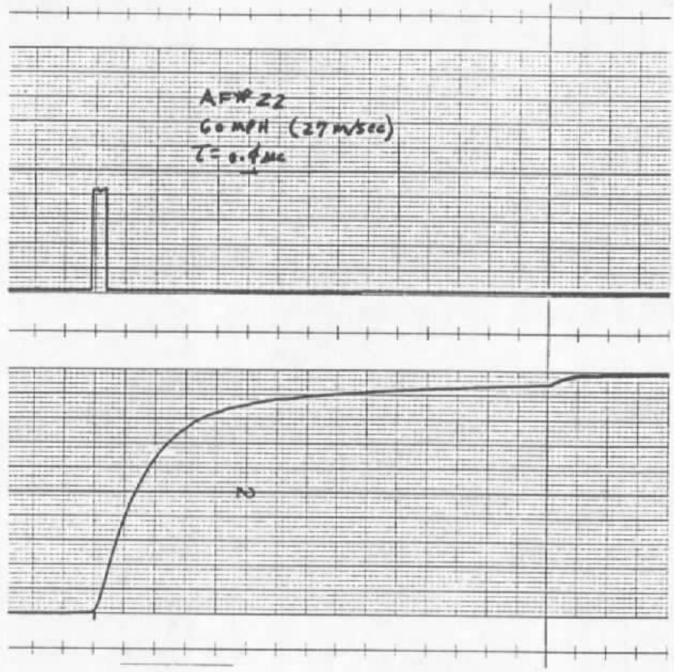


Figure 2.11. Typical Plunge Test Response (27 m/s air). (Subsonic Wind Tunnel)

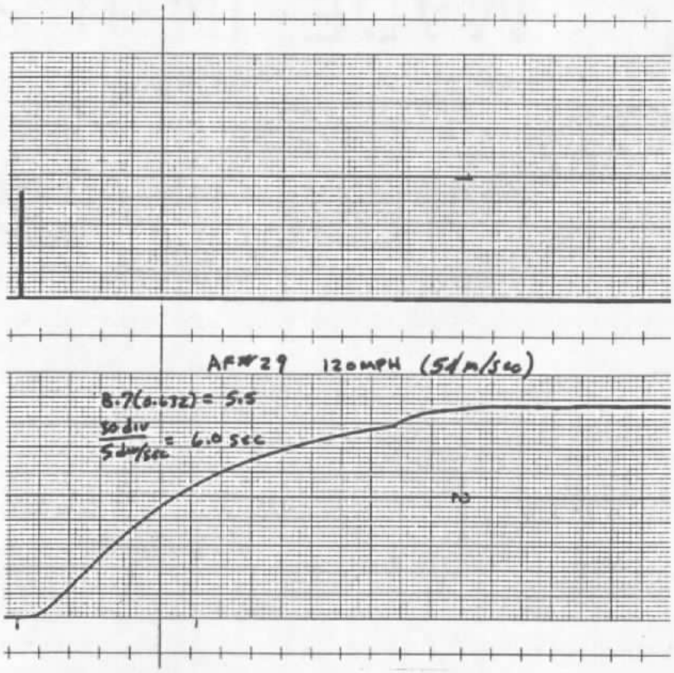


Figure 2.12. Typical Plunge Test Response (54 m/s air). (Subsonic Wind Tunnel)

2.1 Response Time Versus Fluid Flow Characterizations

All of the thermocouples tested in the project exhibited changing response times as test media flow rates and conditions varied. Numerous tests were subsequently performed to determine these effects on thermocouple response. One equation which can be used to express the time constant for temperature sensors in moderate fluid flow (Reynolds numbers ranging from 1000 to 50,000), is as follows:

$$\tau = C_1 + C_2 U^{-0.8} \qquad (2.1)$$

Where C_1 and C_2 are constants, U is the fluid flow rate and τ is the time constant.

To prove this equation satisfactorily describes response characteristics for thermocouples, experimental data for various thermocouples in different flow rates were analyzed and the constants C_1 and C_2 determined. As an example, plunge test data for thermocouple AF#29 taken in flow rates ranging from 0.2 to 1 m/sec in water are shown in Table 2.4. When the corresponding response times are plotted vs. $U^{-0.8}$ (Figure 2.1.1), a linear least square fit can be applied and the constants C_1 and C_2 determined. In the case of AF#29, the equation becomes:

$$\tau = 1.15 \text{ sec} + (0.19 \text{ sec}^2/\text{m}) (U^{-0.8})$$

When response time data for a different thermocouple (AF#09) is obtained, and the same technique used to develop the response time equation, the result is as shown in Figures 2.1.2 and 2.1.3 for water and air. Once the response time equation is determined for a thermocouple or group of thermocouples, evaluation of the response of the thermocouple at any flow rate may be determined if all other conditions are identical. Note that all data used for the fitting of equation (2.1) were obtained with the media temperature remaining relatively constant.

Typical examples illustrating how thermocouple characteristics and test conditions may or may not affect response times are shown for the following cases:

1. Differences in test environment or flow rate can cause large changes in response times (Figure 2.1.4). This represents time constant data vs. $U^{-0.8}$ for the same thermocouple in both water and air. As the film heat transfer coefficient for a thermocouple is lower in air than in water, subsequent response times are correspondingly slower. Also, as flow rates increase, the film heat transfer coefficient improves resulting in faster response times.

TABLE 2.4

Laboratory Plunge Test Results
AF#29 In Water

Flow Rate	Time Constant (sec)
0.2 m/s	1.76
0.3 m/s	1.51
0.6 m/s	1.40
1 m/s	1.38

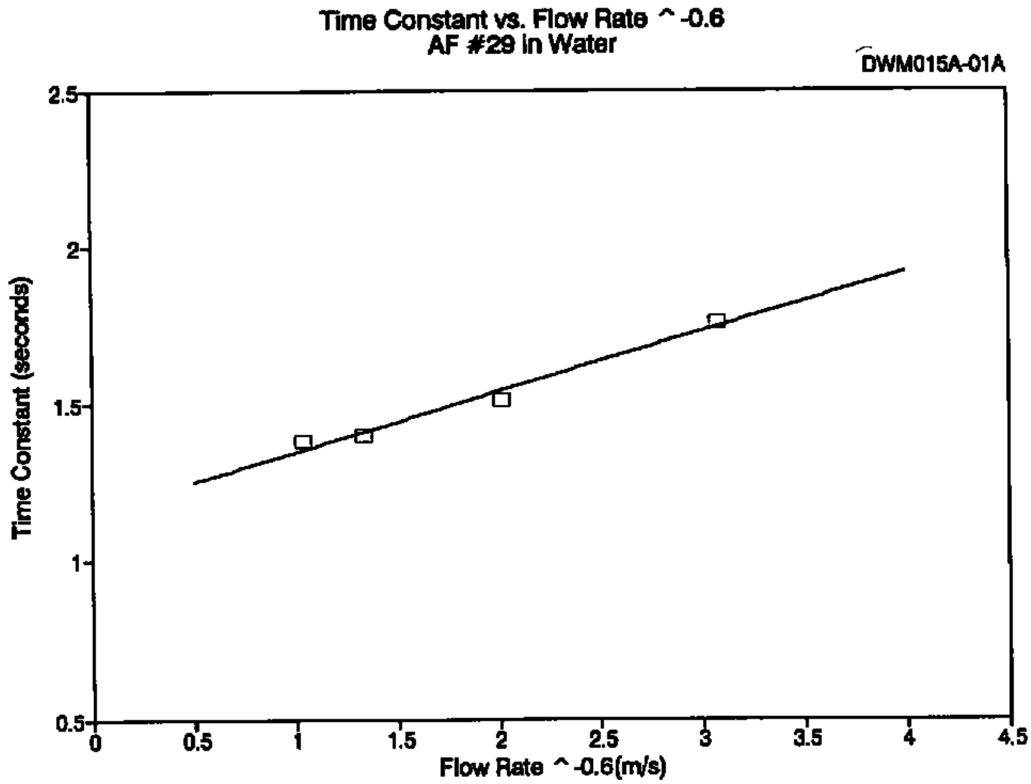


Figure 2.1.1. Time Constant Versus (Flow Rate)$^{-0.6}$ for AF#29 in Water.

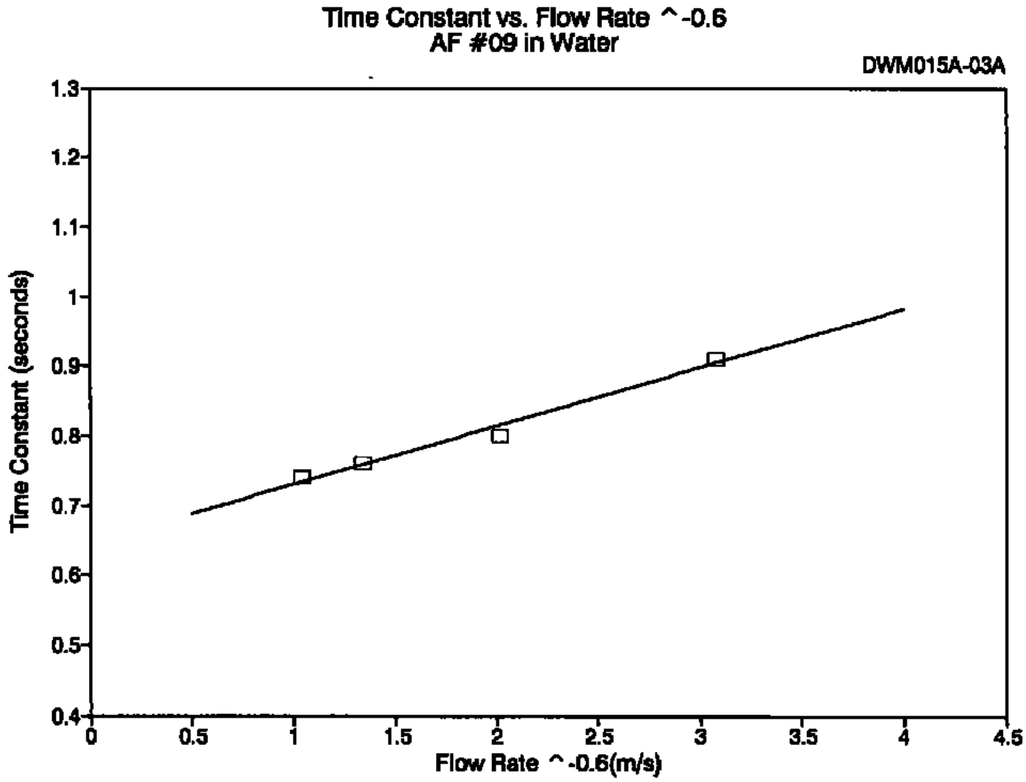


Figure 2.1.2. Time Constant Versus (Flow Rate)$^{-0.6}$ for AF#09 in Water.

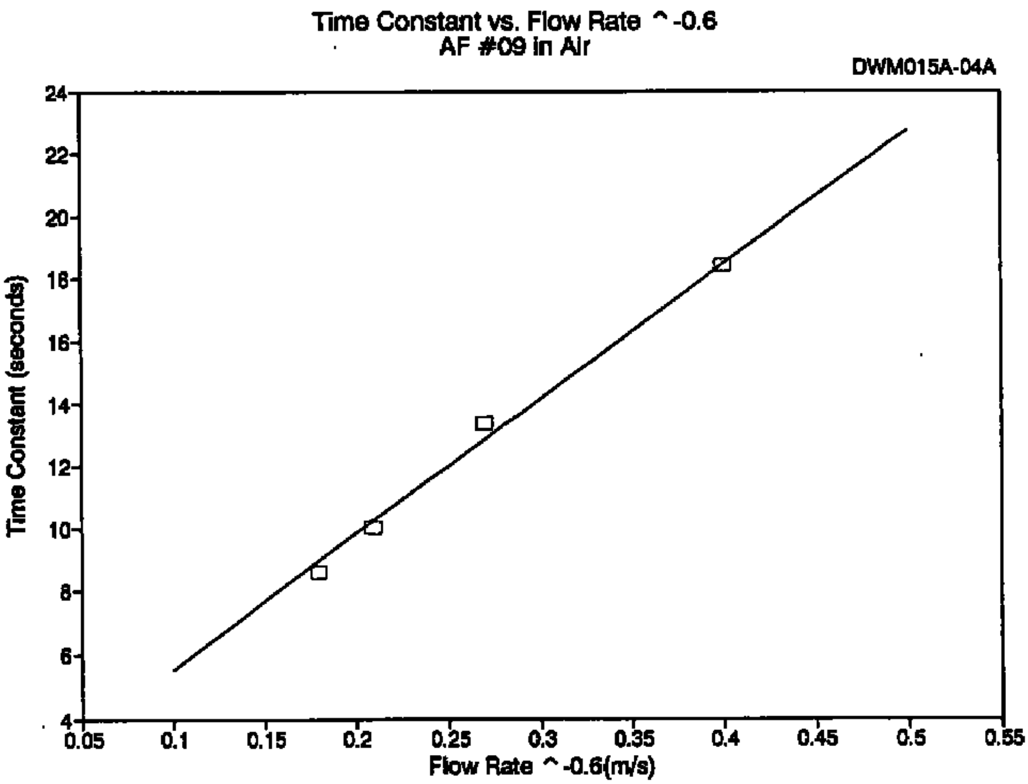


Figure 2.1.3. Time Constant Versus (Flow Rate)$^{-0.6}$ for AF#09 in Air.

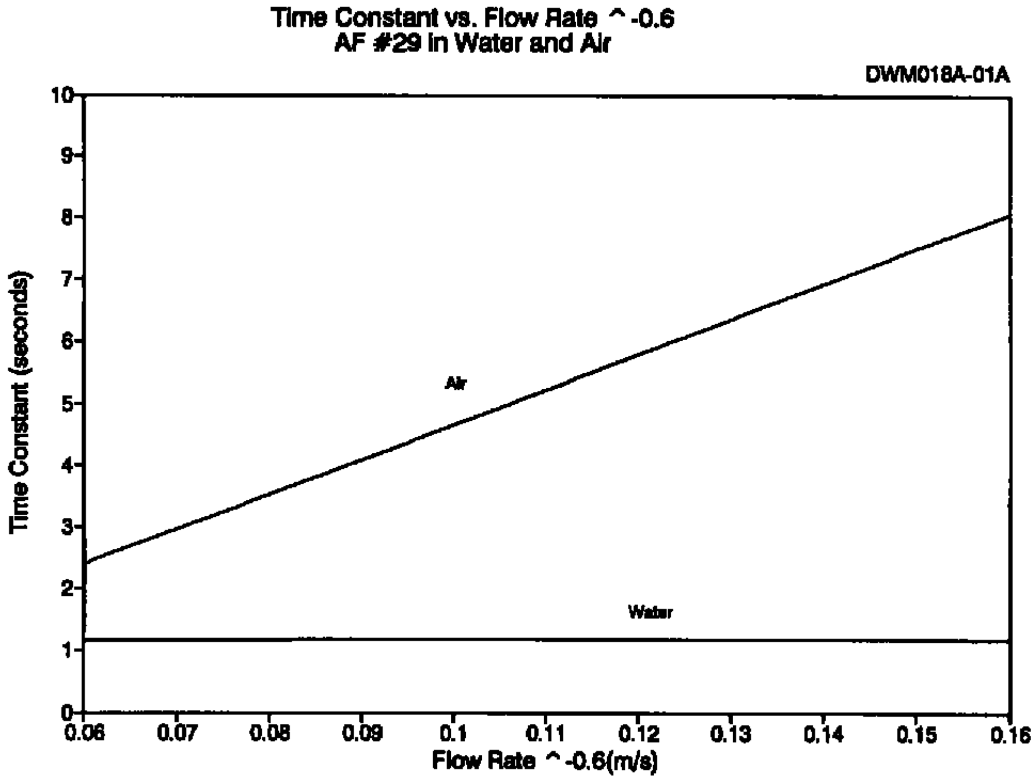


Figure 2.1.4. Changes in Response Due to Different Test Media.

2. The time constant of a thermocouple often depends on its size. Table 2.5 provides time constants of several thermocouples with varying outside diameters placed in a 0.6 m/sec water flow rate. This data is graphically shown in Figure 2.1.5, reflecting how thermocouple size can have a bearing on response time. This effect is also emphasized by Figures 2.1.6 and 2.1.7. These figures represent data for each size thermocouple (for water and air) when they are averaged and plotted versus flow rate. These figures also illustrate the effects of test environment flow rate on thermocouple response.

3. The particular type of thermocouple chosen (E,J,K) will not necessarily have a significant affect on the response time. This is shown in Figure 2.1.8, which shows the averaged response time of each particular type of thermocouple that was tested.

TABLE 2.5

Time Constants as a Function of Thermocouple O.D. 0.6 m/s Water

O.D. (mm)	Time Constant (sec)
6	3.06
5	2.72
3	1.40
2	0.24

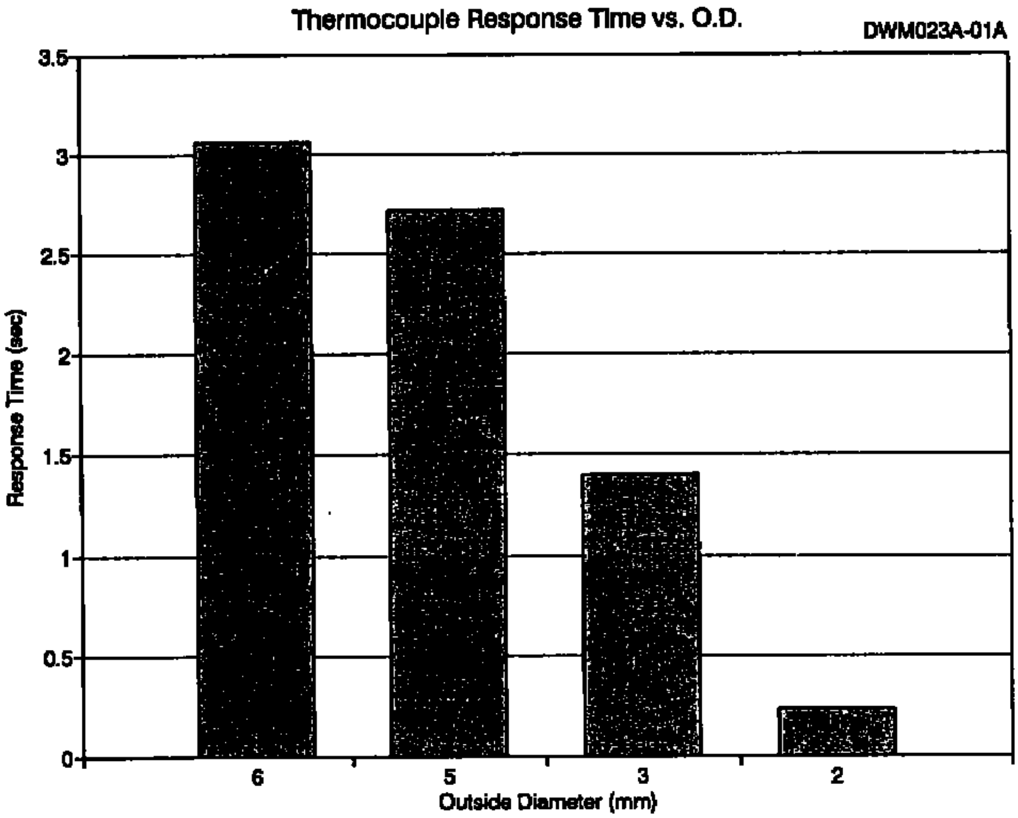


Figure 2.1.5. Time Constant Versus Thermocouple O.D.

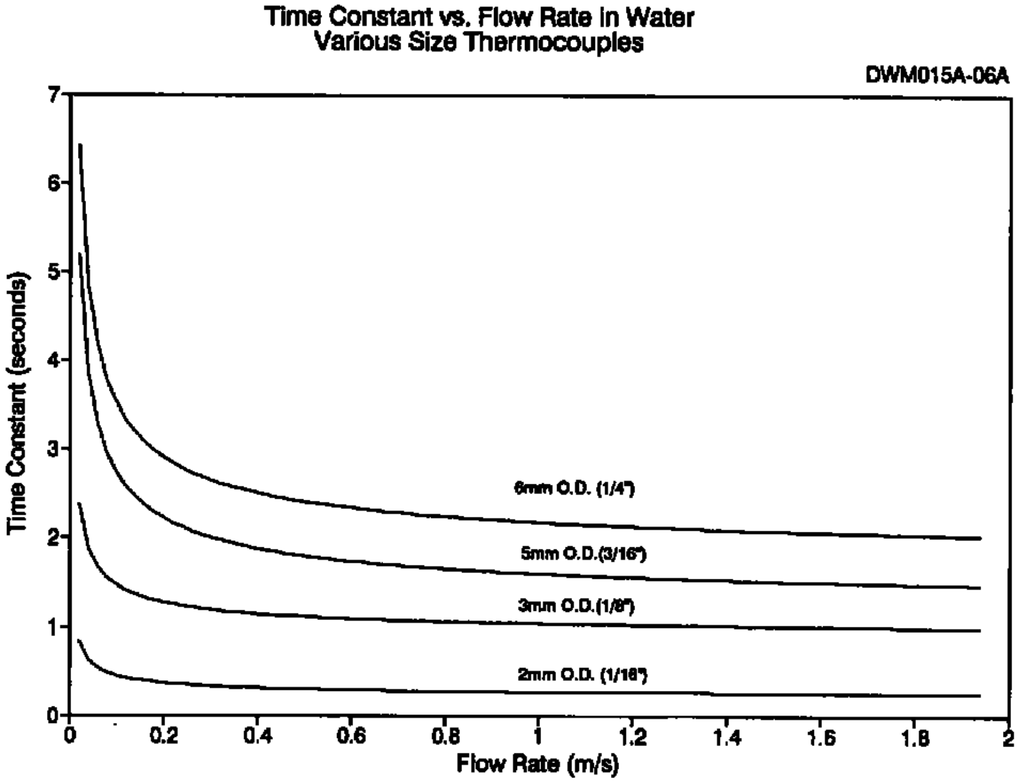


Figure 2.1.6. Time Constant Versus Flow Rate for Various Size Thermocouples in Water.

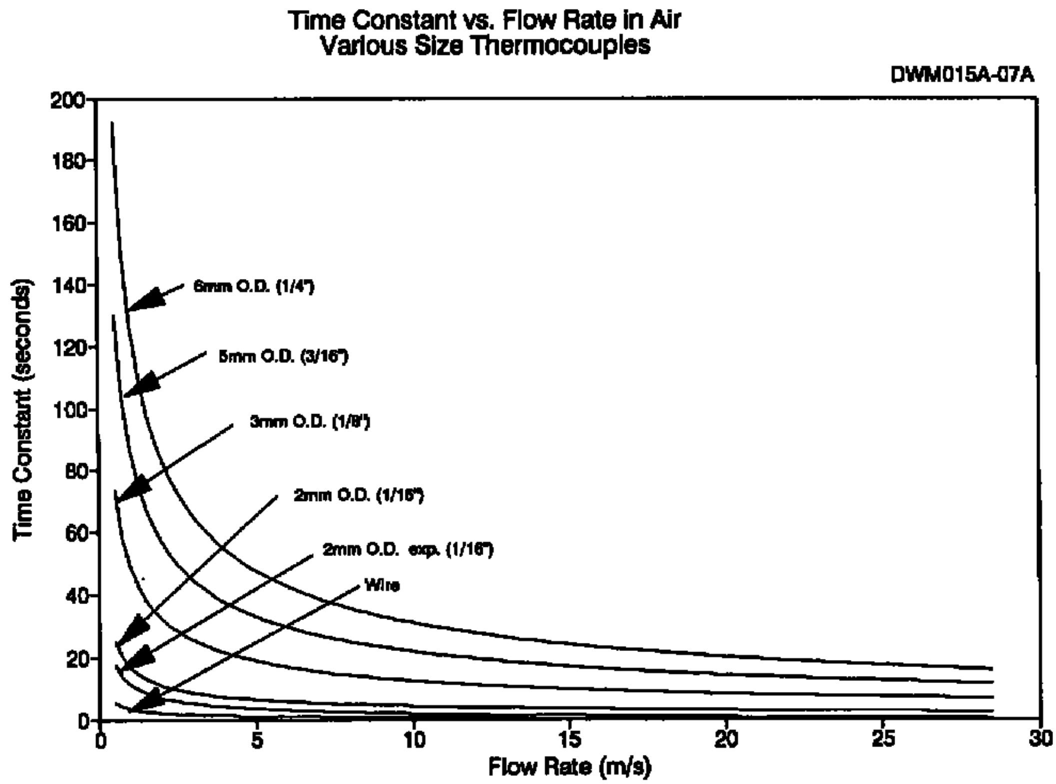


Figure 2.1.7. Time Constant Versus Flow Rate for Various Size Thermocouples in Air.

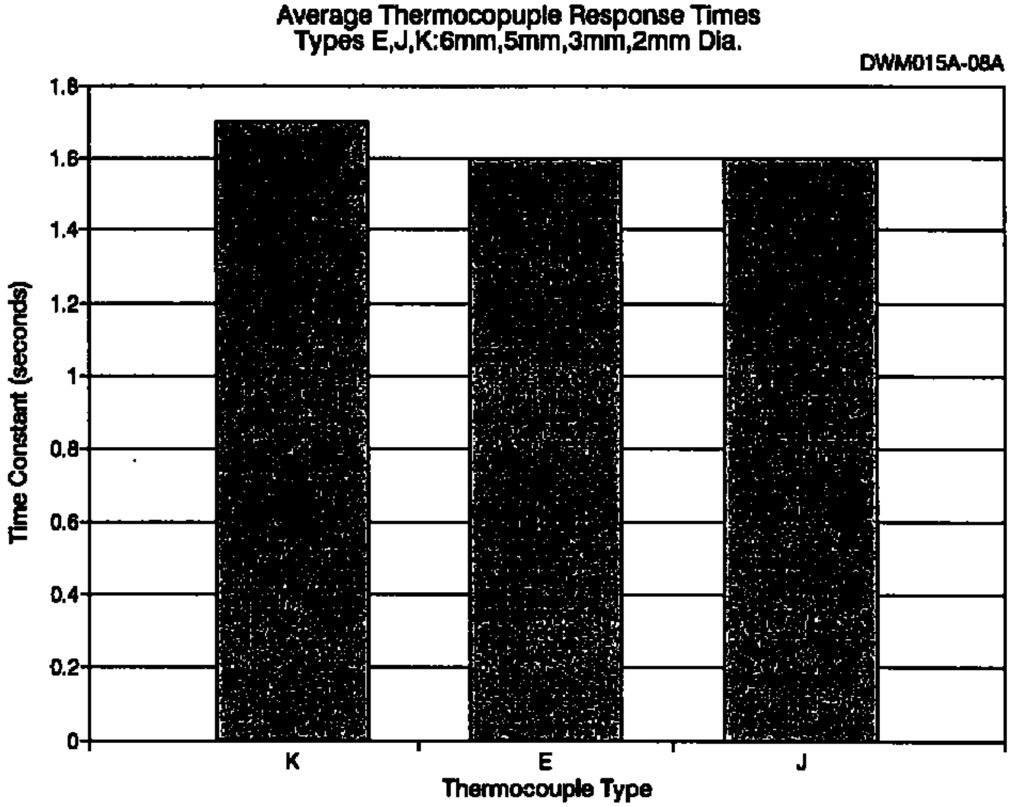


Figure 2.1.8. Averaged Thermocouple Response Times.

3. LCSR VALIDATION RESULTS

To verify the validity of the LCSR method for thermocouples, laboratory tests were performed in both water and air environments and the results compared to baseline plunge test results. The equipment used for the majority of the research is listed in Table 3.1 and shown in Figure 3.1. LCSR validation testing was also performed with the thermocouple LCSR test system manufactured for this project as described in Volume 3; the results of this testing are presented in Section 3.5 of this volume.

The simplified test procedure used to generate LCSR transients for the research project was as follows:

1. Insert the thermocouple to be tested into the test environment and allow the thermocouple EMF output to reach steady-state conditions.
2. Apply the electrical current to heat the thermocouple. Note that the magnitude of current and heating time duration were varied during the project.
3. Terminate the heating current while recording the thermocouple EMF output with the digital data acquisition system and strip chart recorder. The switching from electric current application to recording of thermocouple output is essentially instantaneous.
4. Sample data until steady state conditions are achieved.

Data acquisition parameters (sampling rate, number of points sampled, heating current and heating time) were varied during the research depending on the response of the particular thermocouple under test. Basically, the sampling rate is the time interval per data sample, the heating current is the amount of current applied, the heating time is the duration of the applied current and the number of points sampled determines how many data points are recorded. Sampling rates ranged from about 2 to 50 milliseconds, the number of points sampled ranged from about 1500 to 3000 points, heating currents ranged from 0.25 to 1.5 amperes, and the heating times varied from 5 to 15 seconds.

TABLE 3.1

LCSR Test Equipment

Item	Description
1.	LCSR Test Instrument (AMS ETC-1)
2.	Strip Chart Recorder
3.	Amplifier/Filter
4.	Digital Multimeter
5.	Computer
6.	A/D Converter
7.	Test Media (Rotating Water Bath or Wind Tunnel)

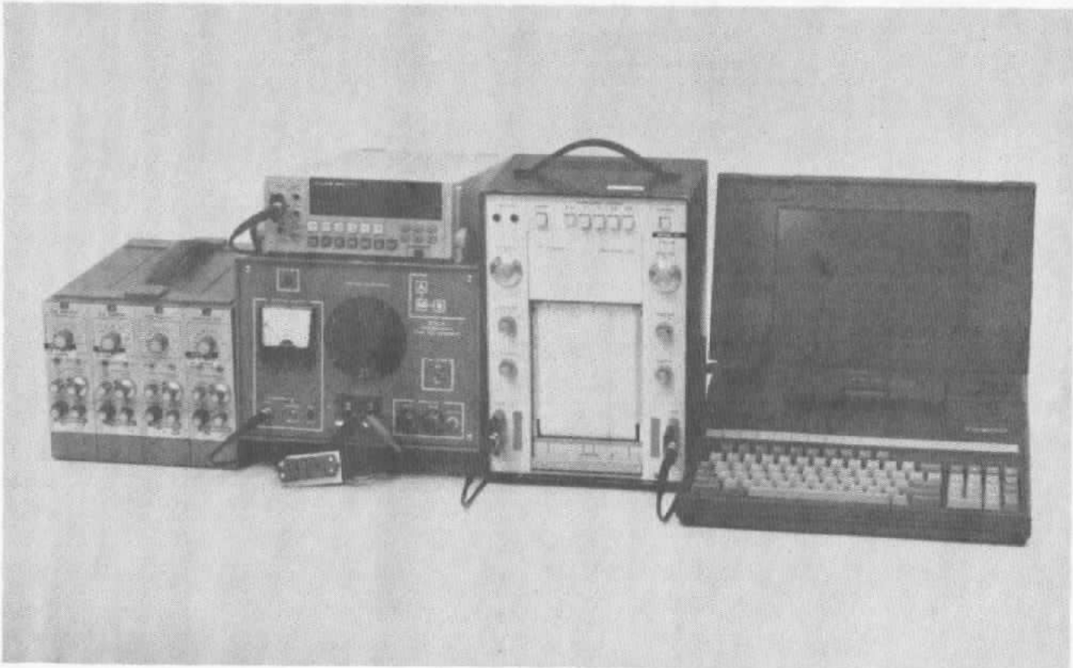


Figure 3.1. LCSR Test Setup.

3.1 LCSR Data Averaging

Due to the thermocouple's inherent nature, LCSR transients often contain irregularities caused by electrical interference, vibration, environmental temperature changes or other hindering effects. An example of a typical thermocouple LCSR transient is shown in Figure 3.1.1, reflecting slight irregularity. To compensate for these effects, an LCSR data averaging routine was used during the research. In essence, the data for ten separate LCSR transients for the same thermocouple were averaged, and the averaged data set analyzed. An example of an averaged data set is shown in Figure 3.1.2, indicating how ten separate data sets (similar to Figure 3.1.1) can be averaged to obtain an acceptable transient for computation of the time constant. Note that all of the LCSR transients presented in this volume (unless otherwise noted) are the average of ten separate sets for a particular thermocouple. The transients have also been inverted for ease of viewing and presentation.

3.2 Analysis Techniques

Once the LCSR data were acquired, several independent analysis methods were examined (some of which were available from developments on RTDs) to evaluate the time constants of the thermocouples. Table 3.2 is a summary of 35 individual LCSR tests performed in both water and air with the calculated results from three separate analysis programs (TSFIT, LST-SQR and XTCA9). This data is graphically represented for two flow conditions (0.6 m/s and 1 m/s) in Figures 3.2.1 and 3.2.2. The first method (TSFIT) was selected (based on these results) as the best analysis technique and used extensively during the research portion of the project and in the microprocessor LCSR analyzer (ESA-1).

In addition to the numerical analysis techniques, all of the LCSR transient data were plotted in semi-logarithmic form. Since the LCSR transient is essentially logarithmic in nature, this assisted in the calculation of time constants. An example of a semi-logarithmic plot of LCSR data is shown in Figure 3.2.3.

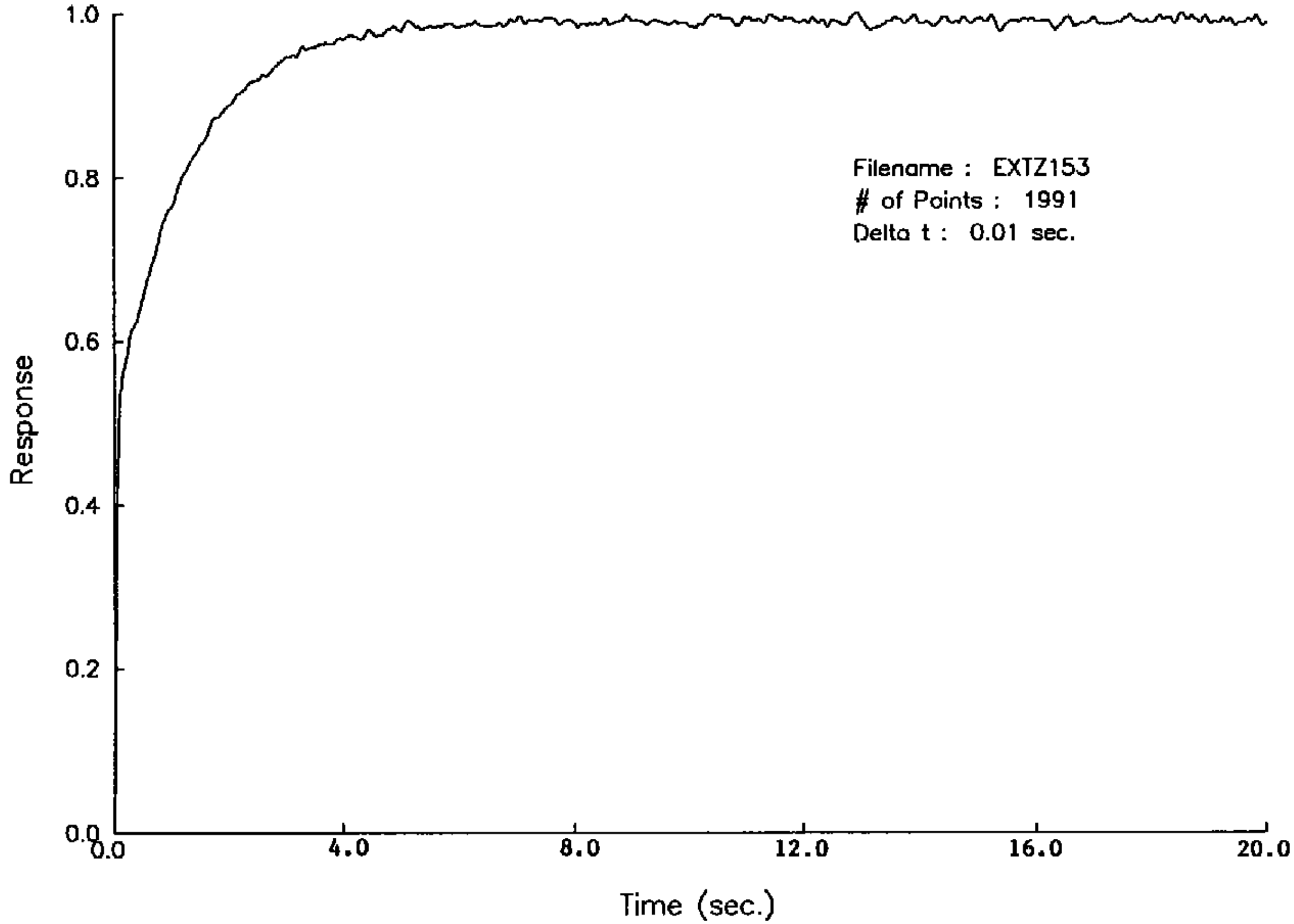


Figure 3.1.1. Raw LCSR Transient for Sensor Tag No. AF #7

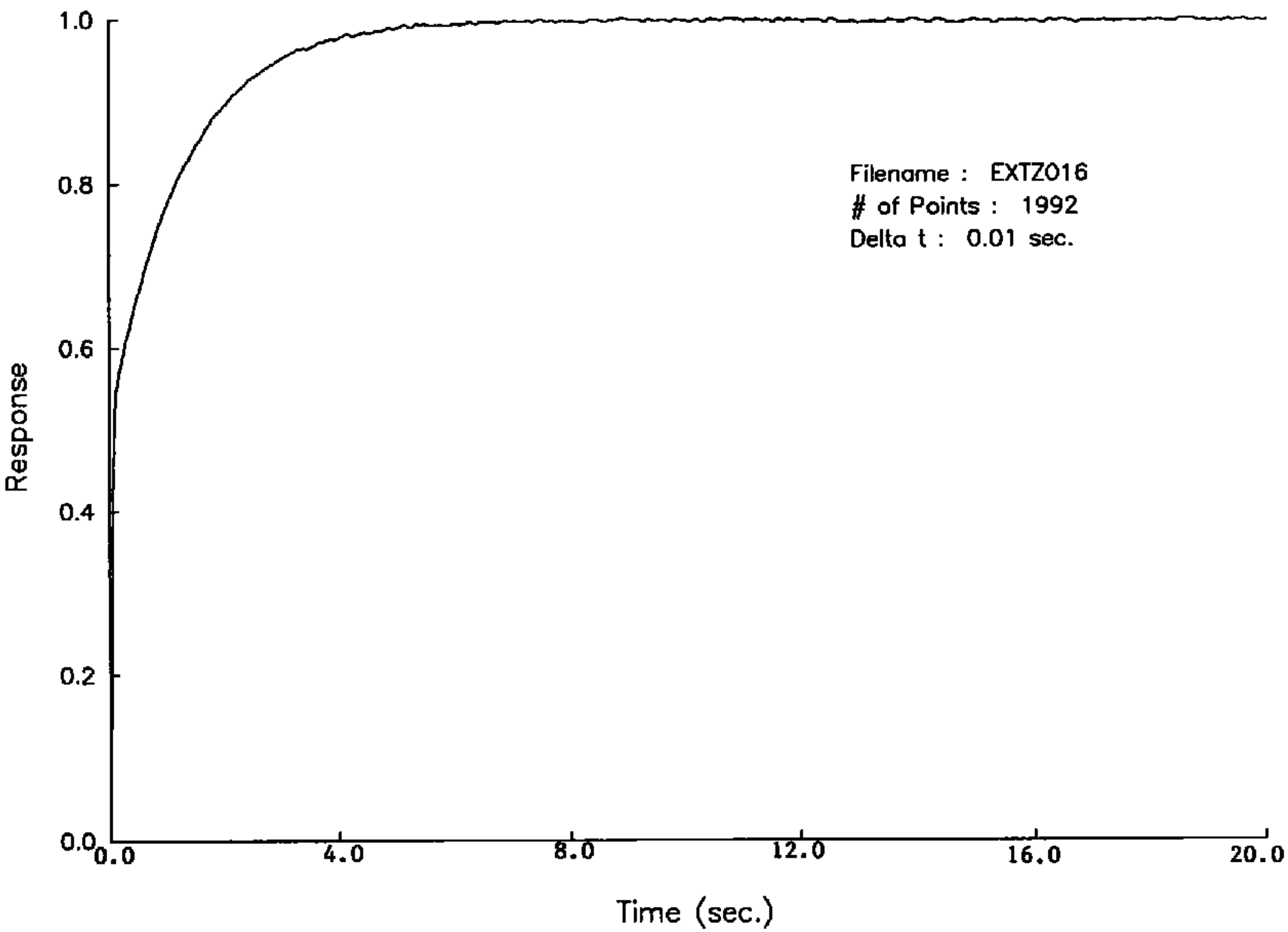


Figure 3.1.2. Averaged LCSR Transient for Sensor Tag No. AF #7 .

Table 3.2

Analysis Summary of Selected Thermocouples

File Name	Tag #	Flow (m/s)	Plunge (sec)	Response Time (sec) Analysis Method TSFIT	LST-SQ	XTCA9
AFP2072	4	0.6	3.1	2.4	2.5	2.5
VER2004	4	1.0	2.7	2.6	2.4	2.1
AFP2066	7	0.6	2.7	2.2	2.9	2.1
VER1006	7	1.0	2.7	2.4	2.2	3.2
VLD1020	7	1.0	2.7	2.2	2.2	2.9
AXT2003	7	14	17.1	27.0	26.0	26.1
AXT1008	7	14	17.1	19.7	17.2	26.6
AFP2060	9	0.6	0.8	0.6	0.6	0.3
VER1008	9	1.0	0.7	0.6	0.5	0.5
VLD2001	9	1.0	0.7	0.9	0.7	1.7
AFP2054	13	0.6	0.3	0.8	0.6	0.8
VER2012	13	1.0	0.3	0.2	0.2	0.2
VLD2021	13	14	0.3	0.3	0.3	0.2
AFP2042	27	0.6	2.0	2.4	2.3	1.9
VER2014	27	1.0	1.9	2.0	1.7	1.6
AXT2010	27	14	17.1	18.4	16.5	34.2*
AFP2036	29	0.6	1.4	1.5	1.5	1.4
VER2016	29	1.0	1.4	1.2	1.2	1.8
VLD2017	29	1.0	1.4	1.2	1.3	.9
AFP2006	36	0.6	1.4	1.0	1.2	0.6
VER2020	36	1.0	1.4	1.2	1.0	0.7
AXT1015	36	14	17.5	22.6	20.2	62.7*
AXT1016	36	14	17.5	22.8	20.5	39.4*
AXT1017	36	14	17.5	18.2	30.0	20.8
VLD2012	36	1.0	1.4	1.5	1.5	1.4
AFP1012	38	0.6	1.9	1.7	2.1	2.3
VER1021	38	1.0	1.8	1.4	1.8	1.6
AFP2024	40	0.6	0.4	0.5	0.5	0.6
VER1022	40	1.0	0.4	0.5	0.3	0.3
AFP2030	43	0.6	0.4	0.5	0.5	0.3
VER1029	43	1.0	0.3	0.4	0.3	0.3
AFP2048	44	0.6	2.1	2.7	2.8	5.1
VER1030	44	1.0	1.9	1.7	2.1	0.16*
AFP2018	46	0.6	2.0	2.3	0.9	0.5
VER1031	46	1.0	1.8	1.5	1.5	1.2

* Major disagreement with the Plunge Test results

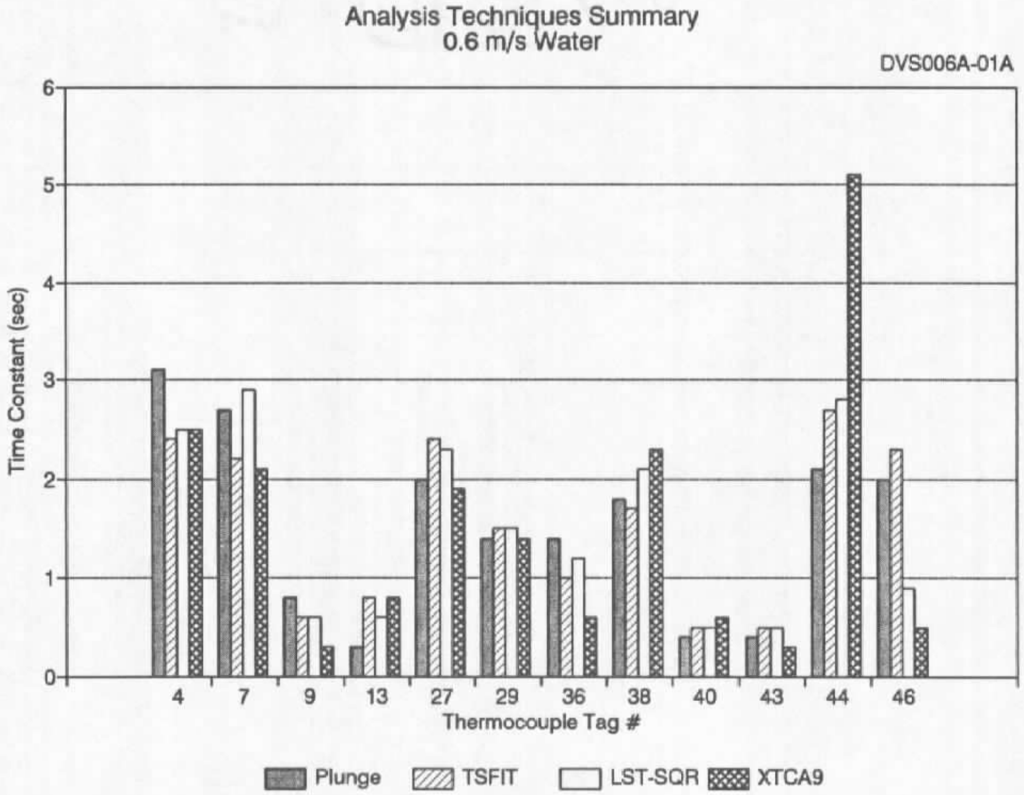


Figure 3.2.1. Computer Program Analysis (0.6 m/s water).

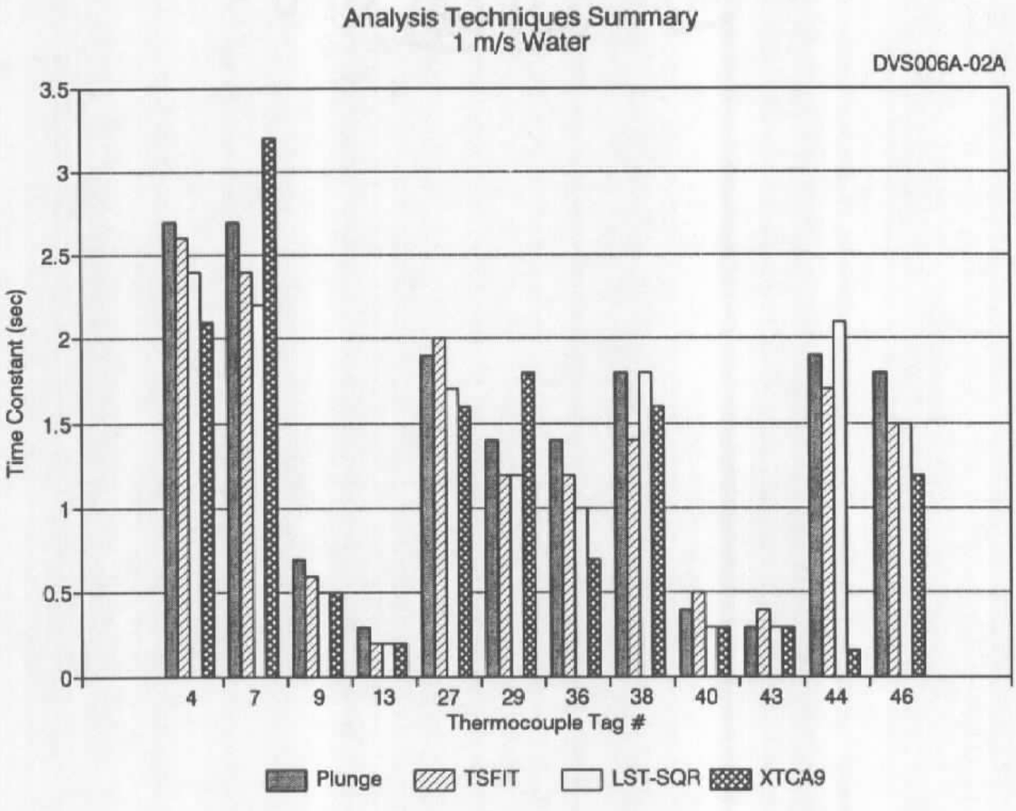


Figure 3.2.2. Computer Program Analysis (1 m/s water).

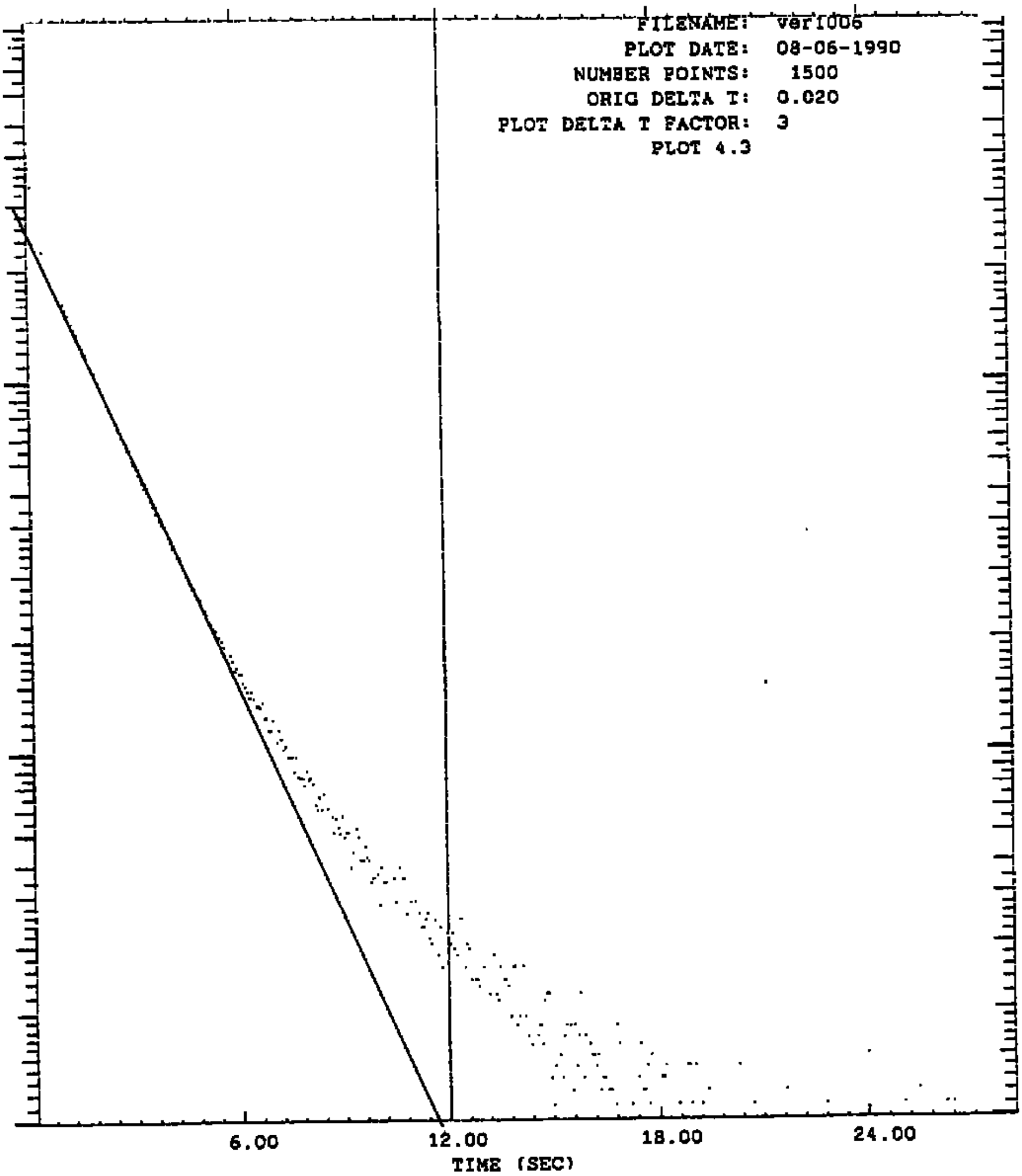


Figure 3.2.3. Typical Semi-Logarithmic Plot of LCSR Data.

3.3 Laboratory Validation of LCSR in Water

For the validation study in water, 12 thermocouples were selected and 1 m/sec flow used. The thermocouples where chosen based upon previous stable performance and represented a broad variety of sizes and types. The results of these tests are given in Table 3.3, and graphically presented in Figure 3.3.1.

Typical averaged thermocouple LCSR transients for water and their corresponding semi-logarithmic plots are shown in Figures 3.3.2 through 3.3.7 for type E, J, and K thermocouples.

3.4 Laboratory Validation of LCSR in Air

For the validation of thermocouple LCSR in air, 15 thermocouples were selected. In this case, many of the same thermocouples used for the validation study in water were again used. Each of the thermocouples was subjected to 14 m/sec air flow in the AMS air loop. The results of these tests are shown in Table 3.4 with a graphical representation shown in Figure 3.4.1. Examples of LCSR test data in air and associated semi-logarithmic plots are given in Figures 3.4.2 through 3.4.7 for type E, J, and K thermocouples.

3.5 Laboratory Validation of Manufactured Equipment

The thermocouple LCSR test system developed for this project (explained in detail in Volume 3) was successfully tested to verify the results it produced were accurate. Validation testing of the equipment was performed in both water and air using several relatively stable thermocouples. Test parameters (heating current, heating time, number of points sampled, and sampling rate) were optimized using developed procedures to obtain the most consistent results. The results of the testing in water are shown in Table 3.5 and graphed in Figure 3.5.1. The air results are shown in Table 3.6 and Figure 3.5.2.

TABLE 3.3

Thermocouple LCSR Test Results
Initial Validation 1 m/s Water

Tag#/Size	Plunge (sec)	LCSR (sec)	|Difference| (sec)
TYPE E			
AF #44/6mm	1.87	1.60	0.27
AF #27/5mm	1.91	1.82	0.09
AF #29/3mm	1.38	1.31	0.07
AF #43/2mm	0.34	0.36	0.02
TYPE J			
AF #46/6mm	1.84	1.48	0.36
AF #36/5mm	1.36	1.09	0.27
AF #38/3mm	1.76	1.35	0.41
AF #40/2mm	0.42	0.42	0.00
Type K			
AF # 4/6mm	2.74	2.72	0.02
AF # 7/5mm	2.69	2.38	0.31
AF # 9/3mm	0.74	0.58	0.16
AF #13/2mm	0.26	0.16	0.10

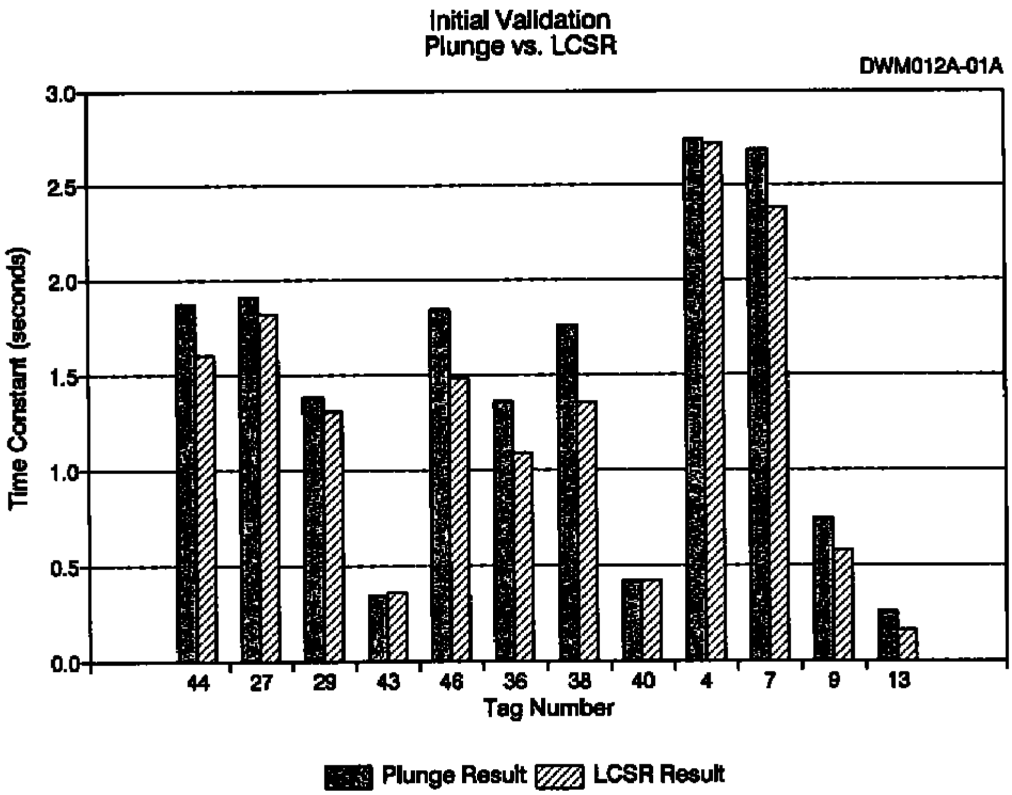


Figure 3.3.1. Results of Initial Validation in Water (1 m/s).

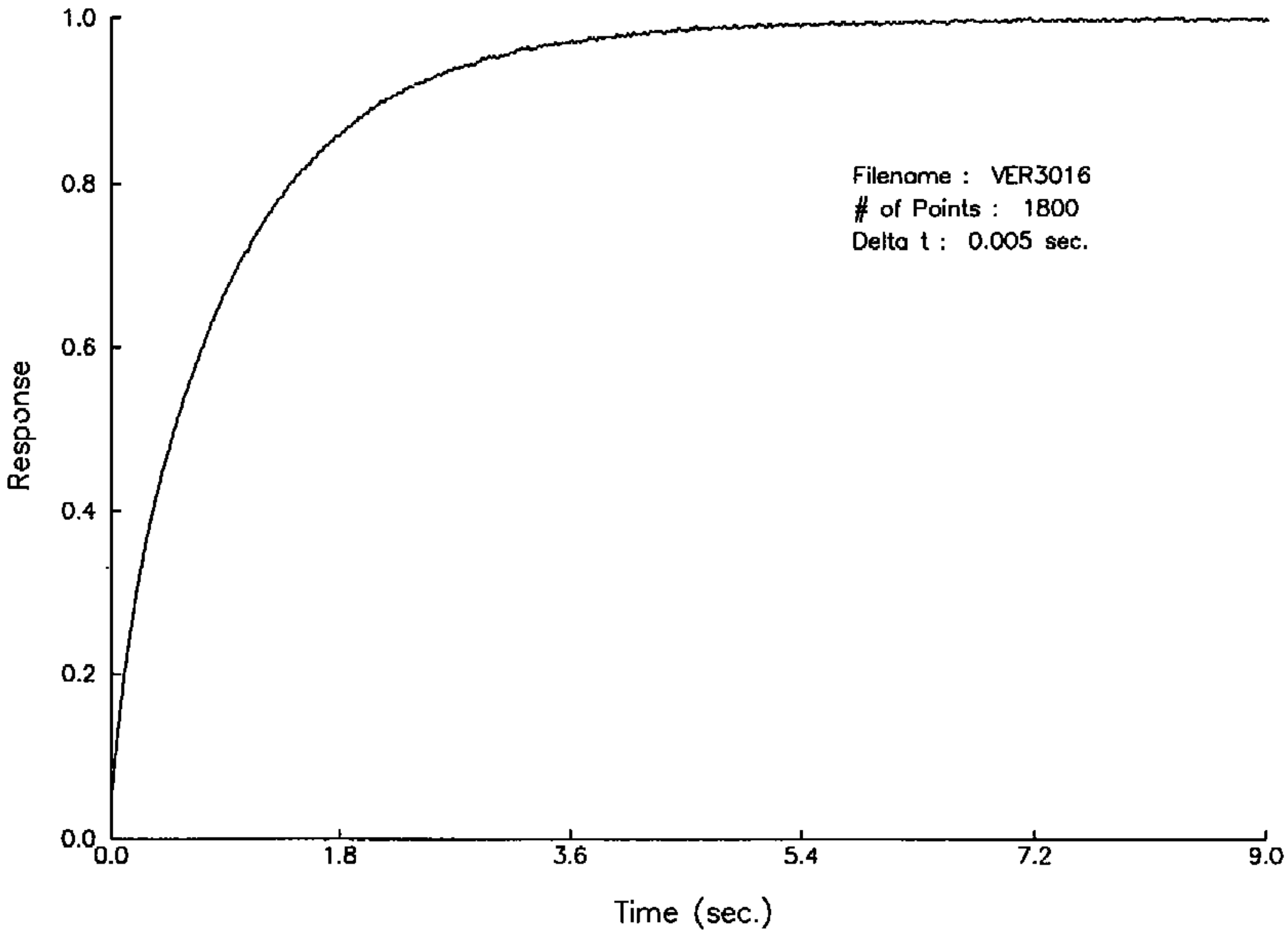


Figure 3.3.2. Averaged LCSR Transient for Sensor Tag No. AF #29 in water .

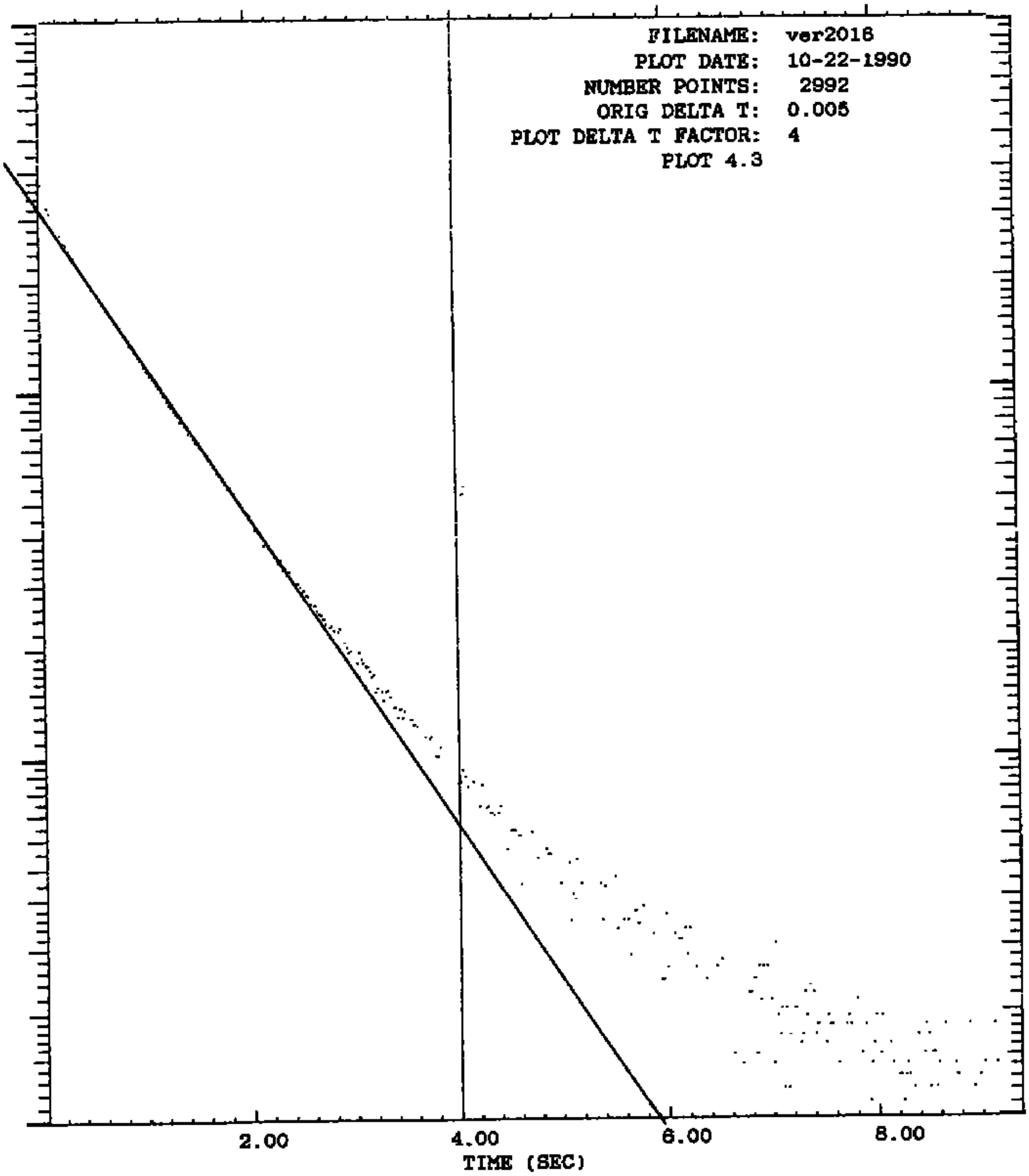


Figure 3.3.3. Semi-Logarithmic Plot for AF#29 in Water.

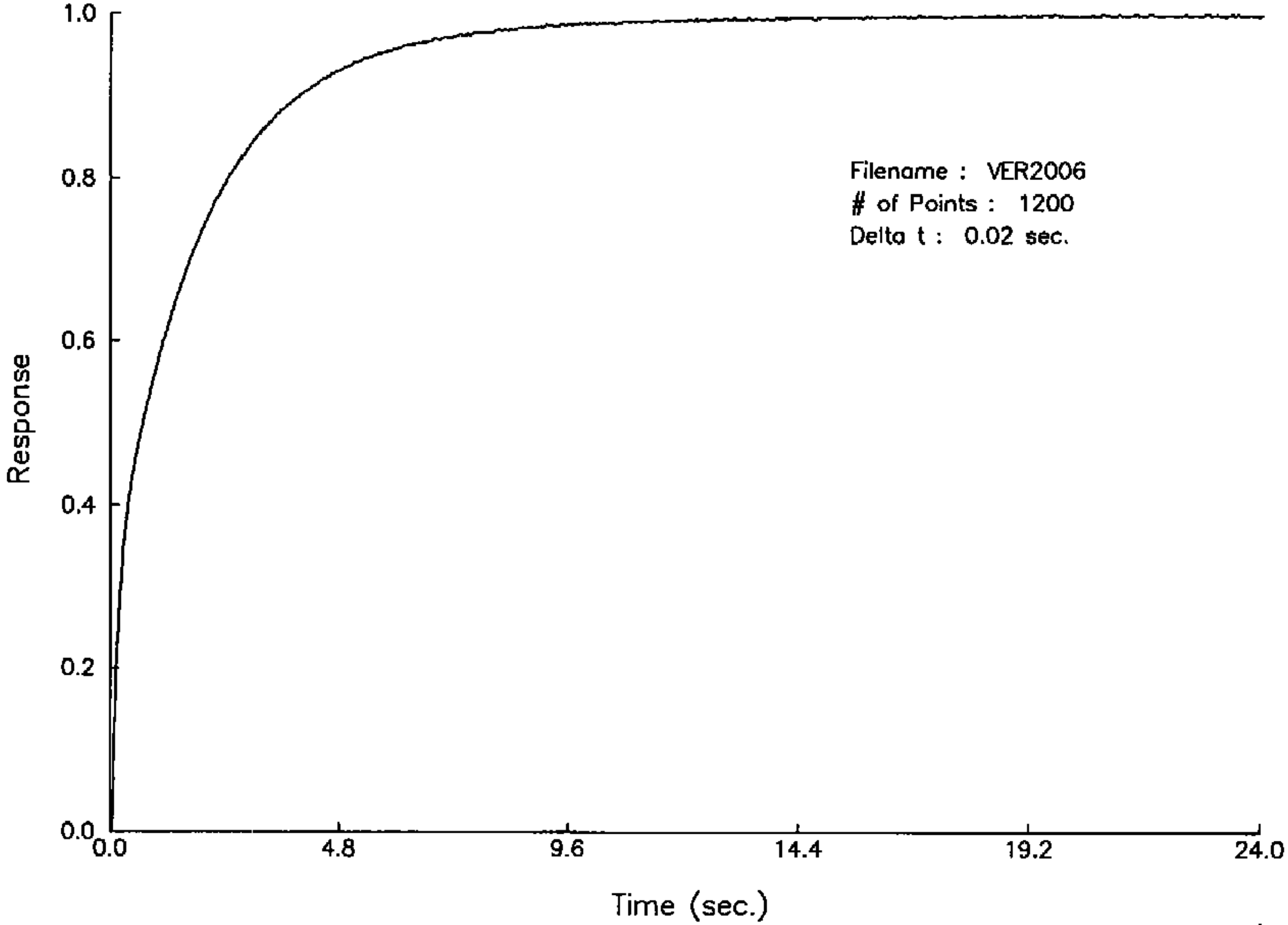


Figure 3.3.4. Averaged LCSR Transient for Sensor Tag No. AF #07 in water .

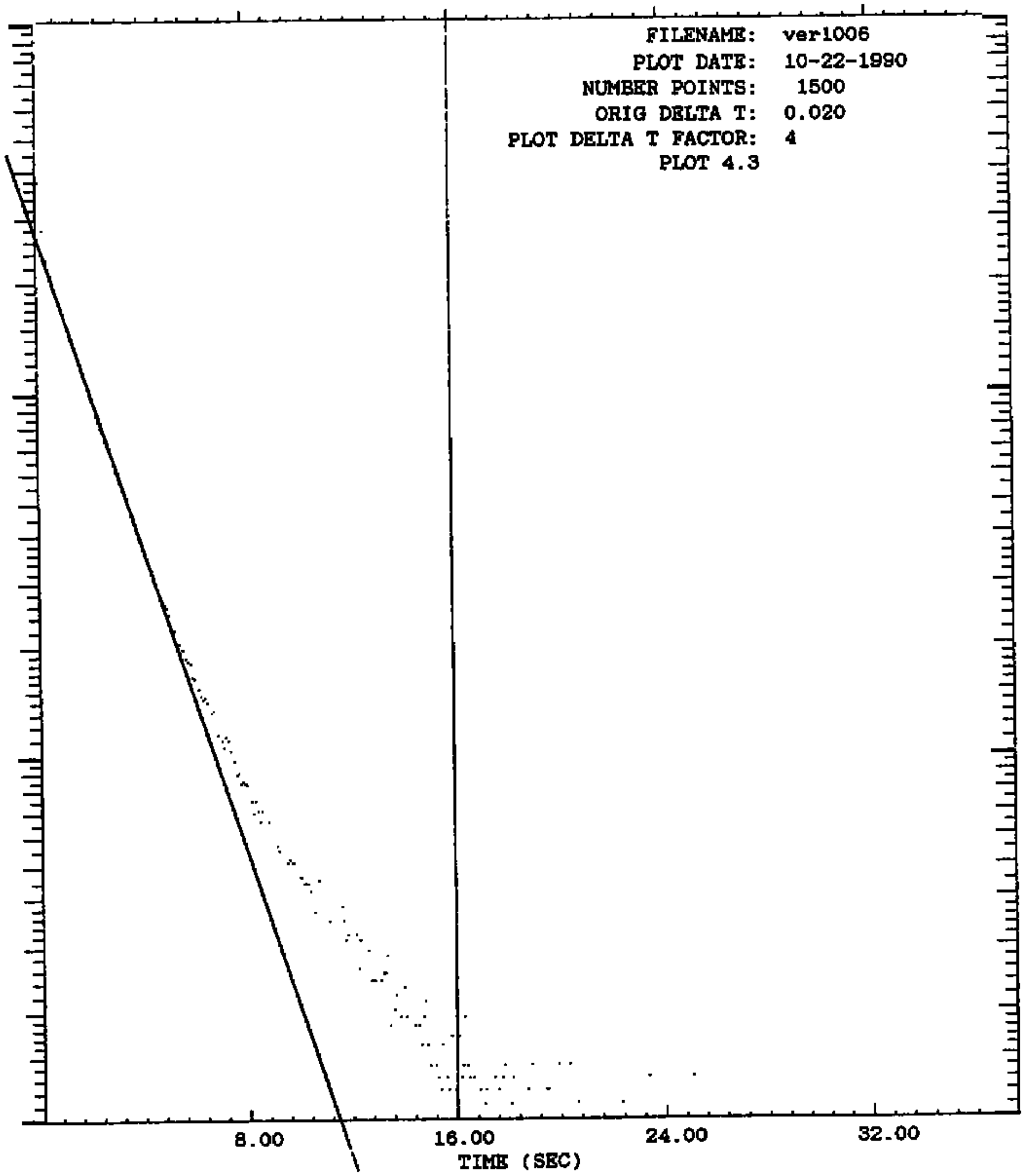


Figure 3.3.5. Semi-Logarithmic Plot of AF#07 in Water.

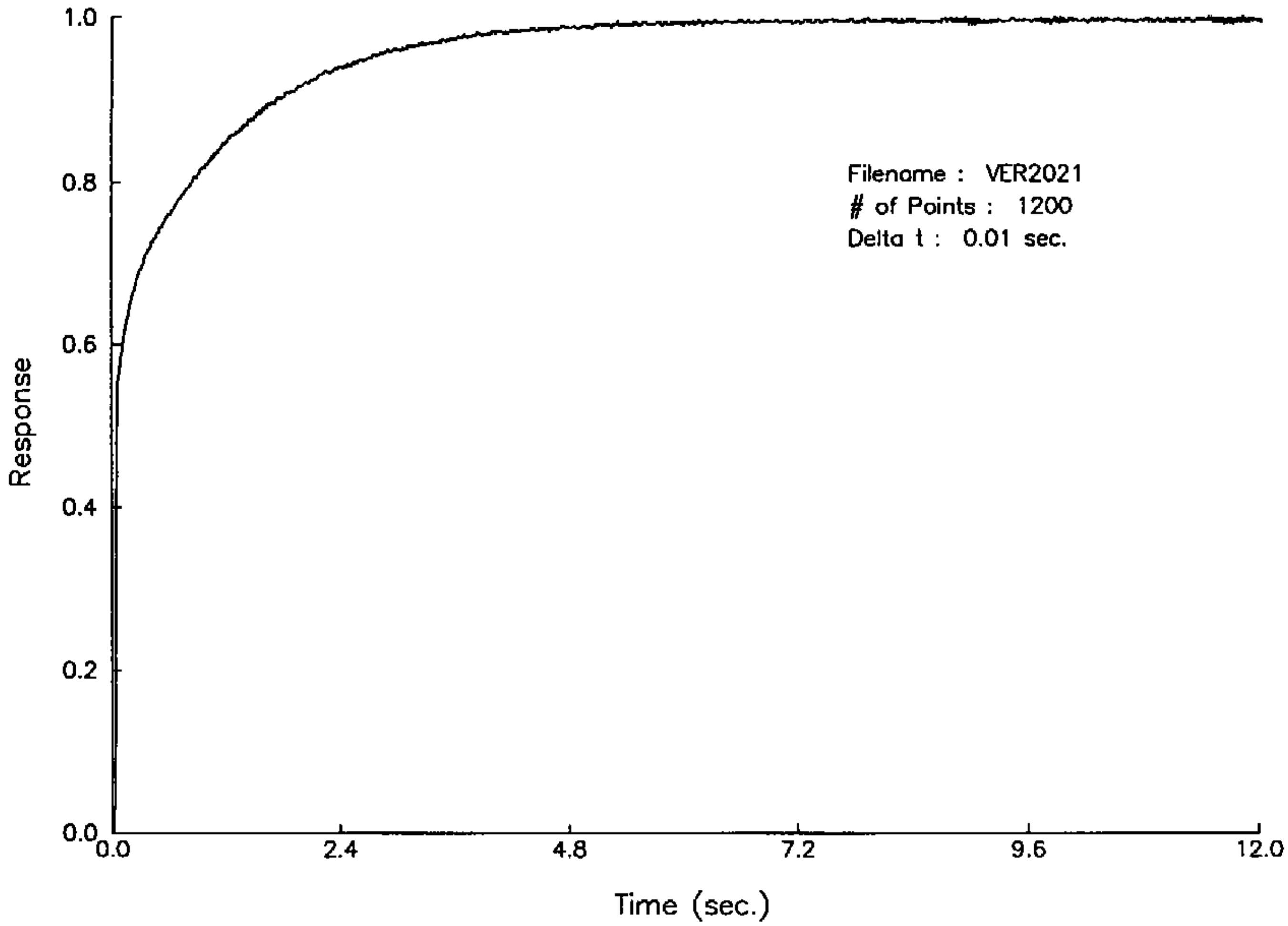


Figure 3.3.6. Averaged LCSR Transient for Sensor Tag No. AF #38 in water .

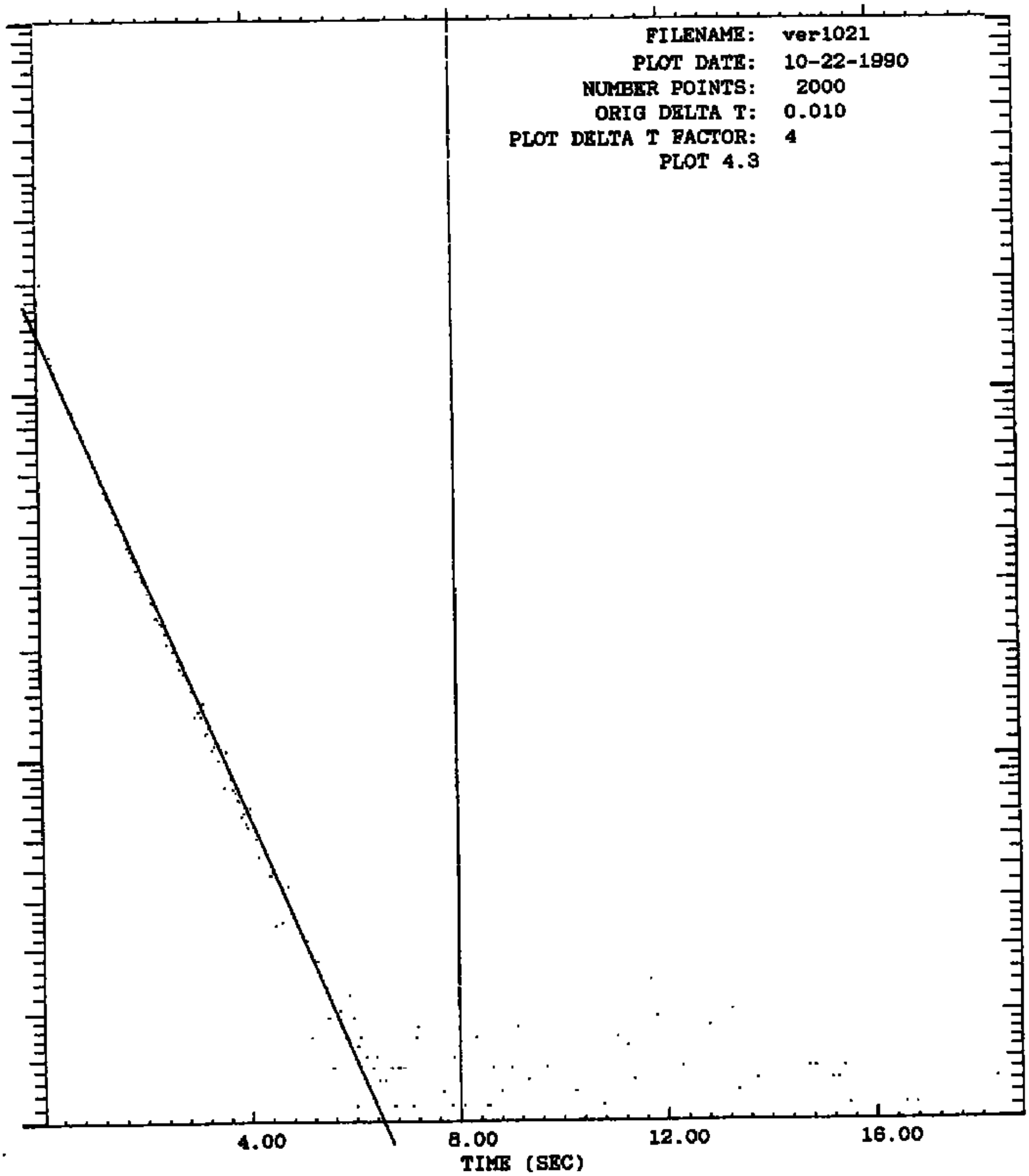


Figure 3.3.7. Semi-Logarithmic Plot of AF#38 in Water.

TABLE 3.4

**Thermocouple LCSR Test Results
Air Loop Validation 14 m/sec Air**

Tag #	Plunge (sec)	LCSR (sec)	|Difference| (sec)
Type E			
51	1.12	0.82	0.30
43	3.88	4.50	0.62
29	10.55	12.10	1.55
27	17.10	22.33	5.23
44	23.90	32.60	8.70
TYPE K			
52	1.28	1.20	0.80
40	3.20	3.80	0.60
38	9.90	12.09	2.19
36	17.50	21.28	3.78
46	24.85	35.90	11.05
TYPE J			
22	0.49	0.30	0.19
13	3.66	3.85	0.19
9	10.03	11.30	1.27
7	17.13	23.00	5.87
4	25.15	29.70	4.55

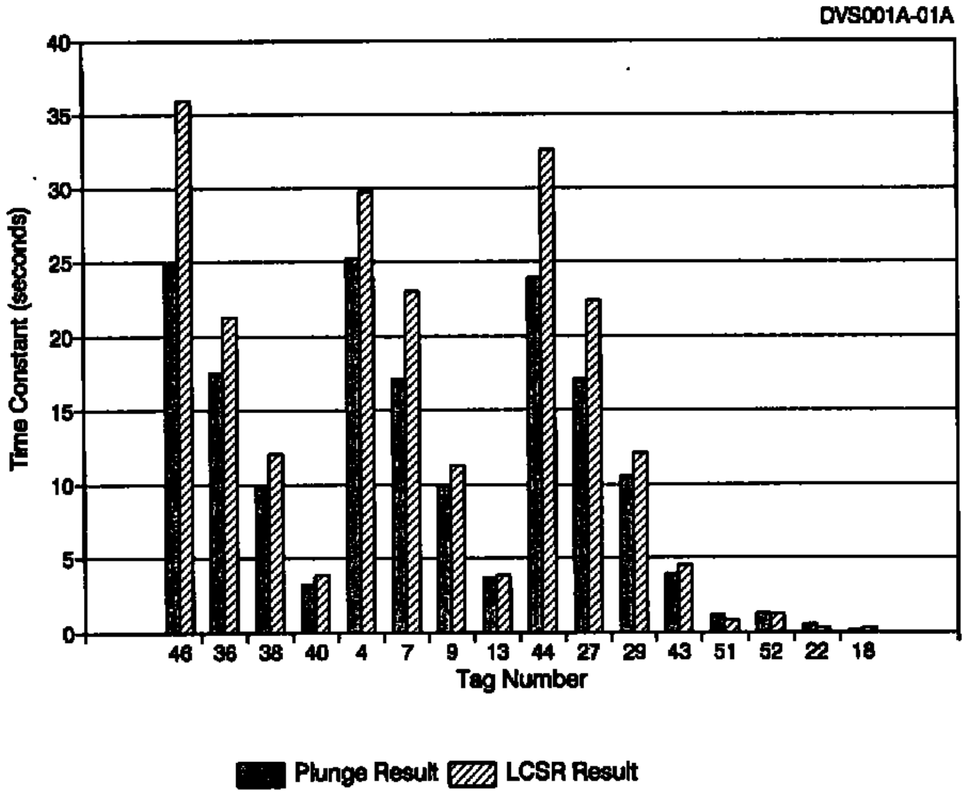


Figure 3.4.1. Results of Initial Validation in Air.

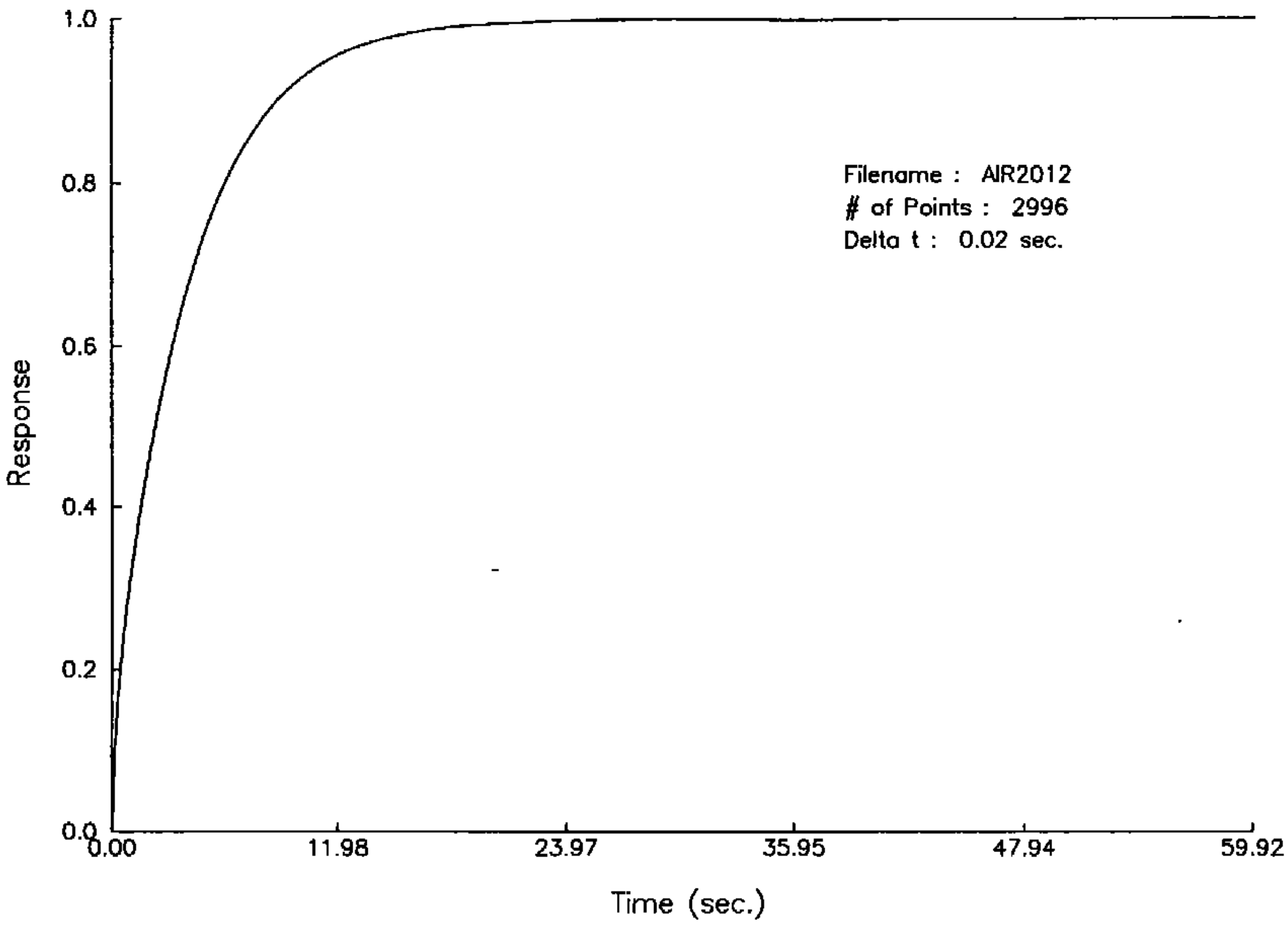


Figure 3.4.2. Averaged LCSR Transient for Sensor Tag No. AF #43 in Air .

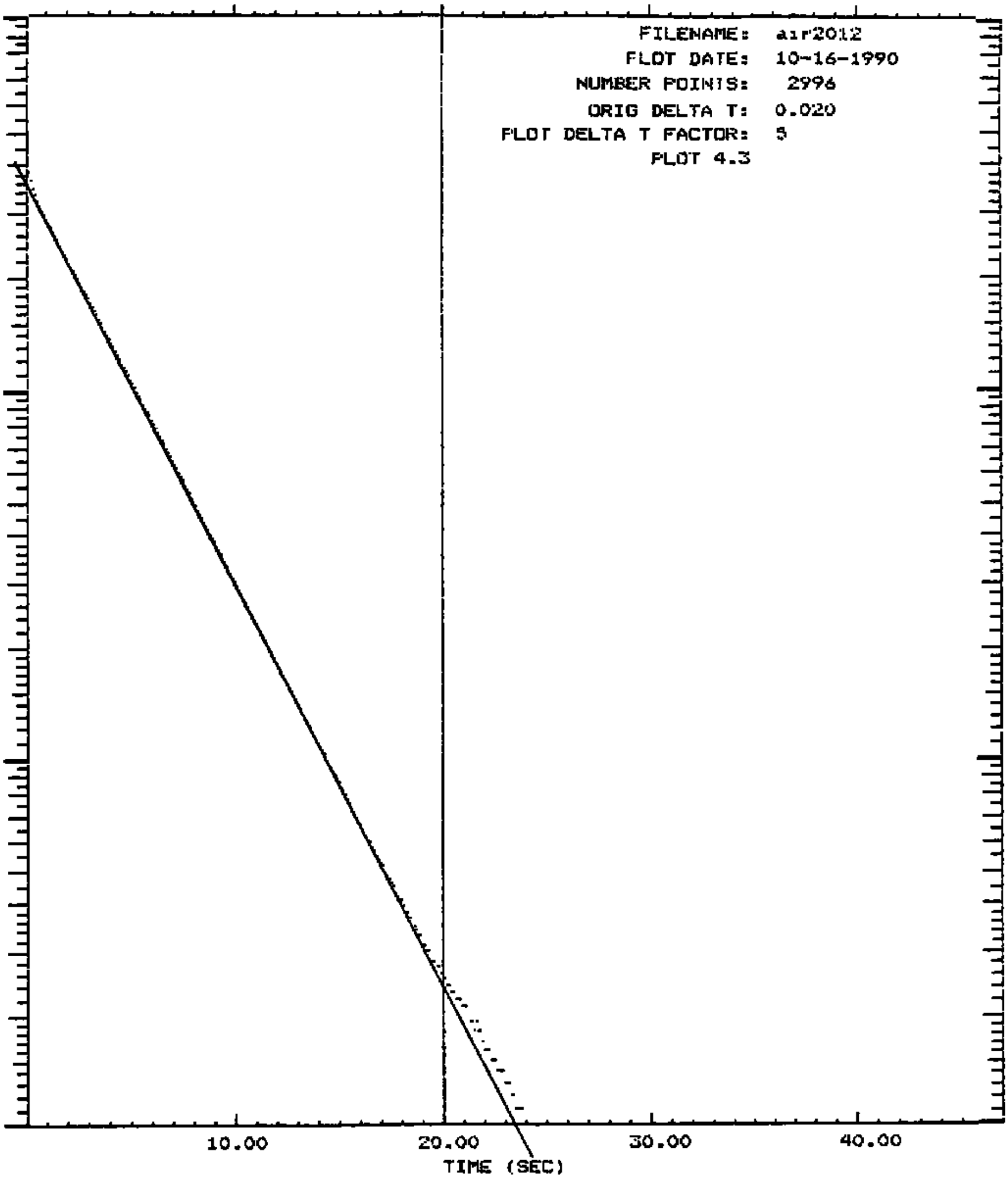


Figure 3.4.3. Semi-Logarithmic Plot of AF#43 in Air.

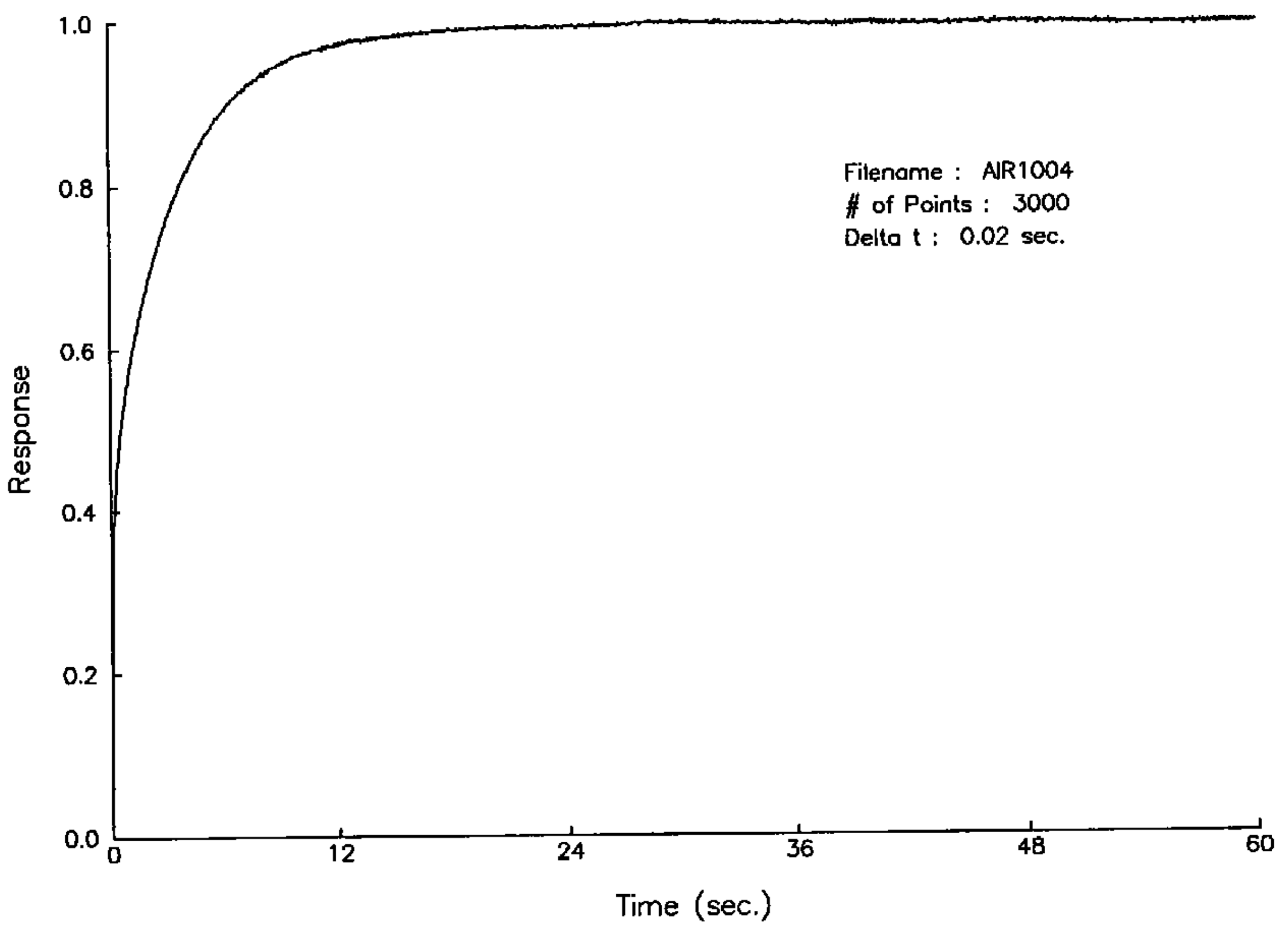


Figure 3.4.4. Averaged LCSR Transient for Sensor Tag No. AF #40 in Air

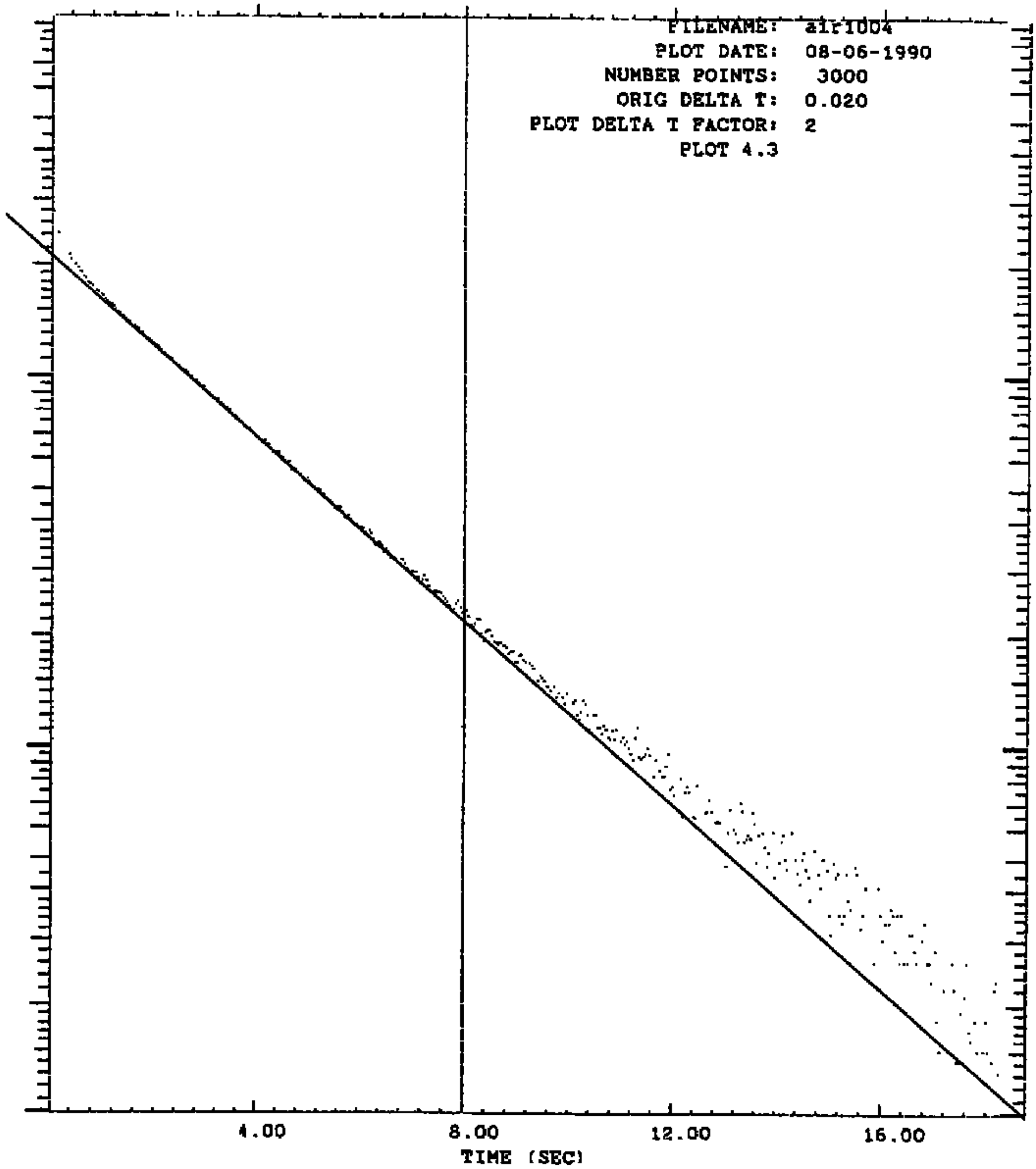


Figure 3.4.5. Semi-Logarithmic Plot of AF#40 in Air.

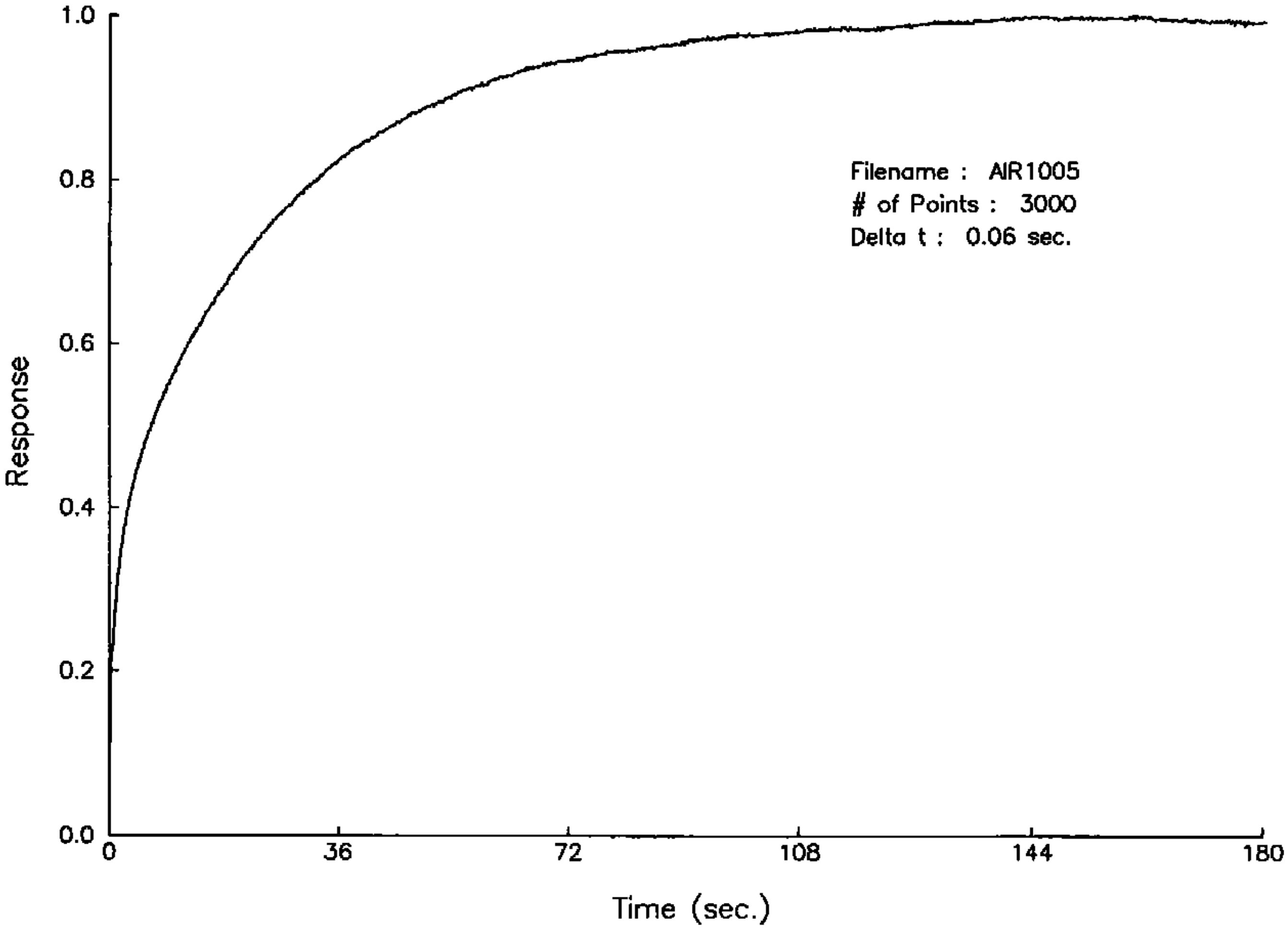


Figure 3.4.6 Averaged LCSR Transient for Sensor Tag No. AF #04 in Air .

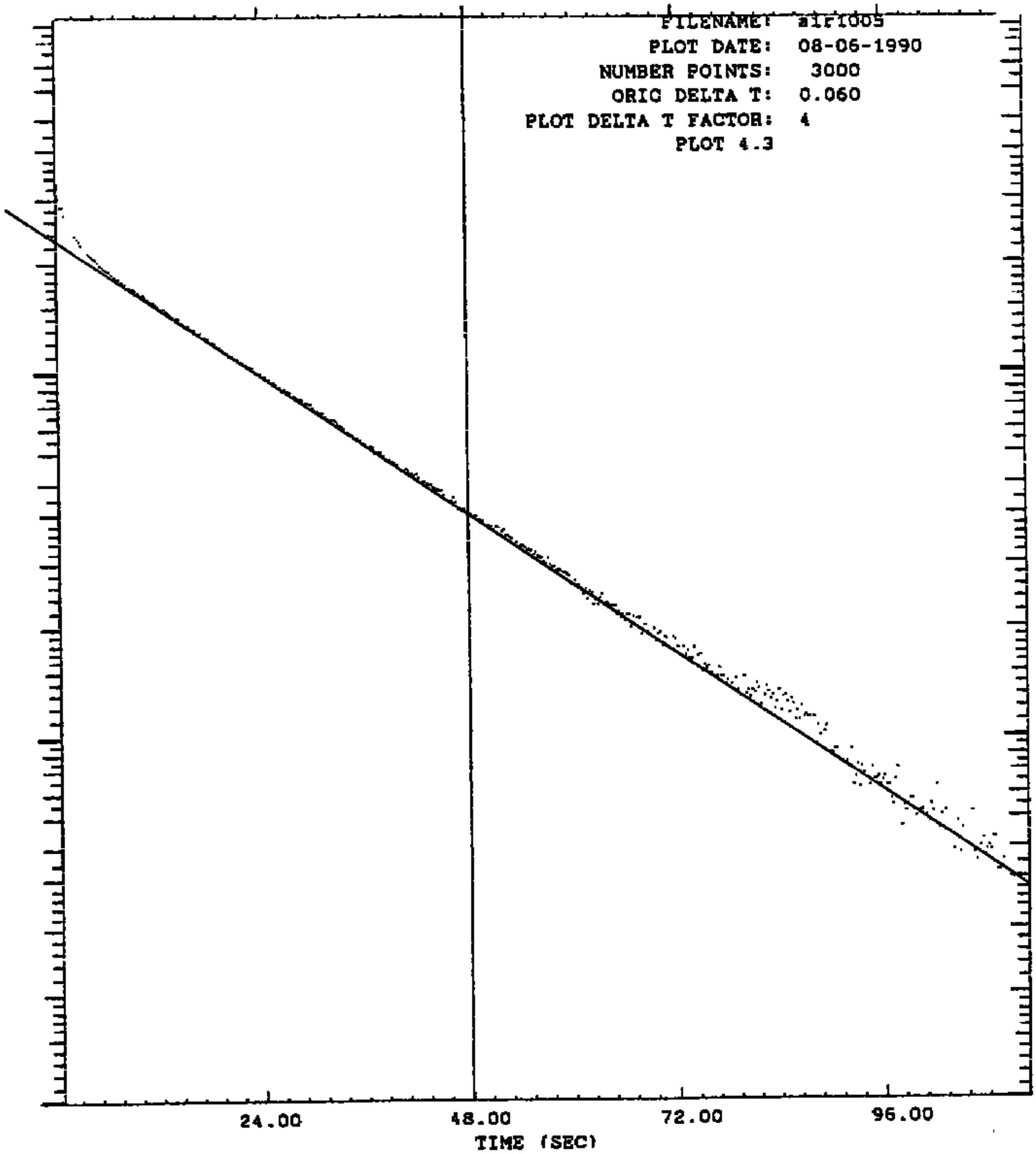


Figure 3.4.7. Semi-Logarithmic Plot for AF#04 in Air.

TABLE 3.5

Manufactured Equipment Validation Results
(0.6 m/sec water)

TC Tag #	Plunge Result (sec)	LCSR Result (sec)	|Difference| (sec)
29	1.40	1.10	0.30
27	2.00	1.99	0.01
43	0.37	0.37	0.00
44	2.10	2.19	0.09
46	1.98	2.39	0.41
36	1.43	1.33	0.10
38	1.90	1.98	0.08
40	0.43	0.43	0.00
04	3.06	2.83	0.23
07	2.72	2.96	0.24
09	0.76	0.49	0.27
13	0.27	0.29	0.02

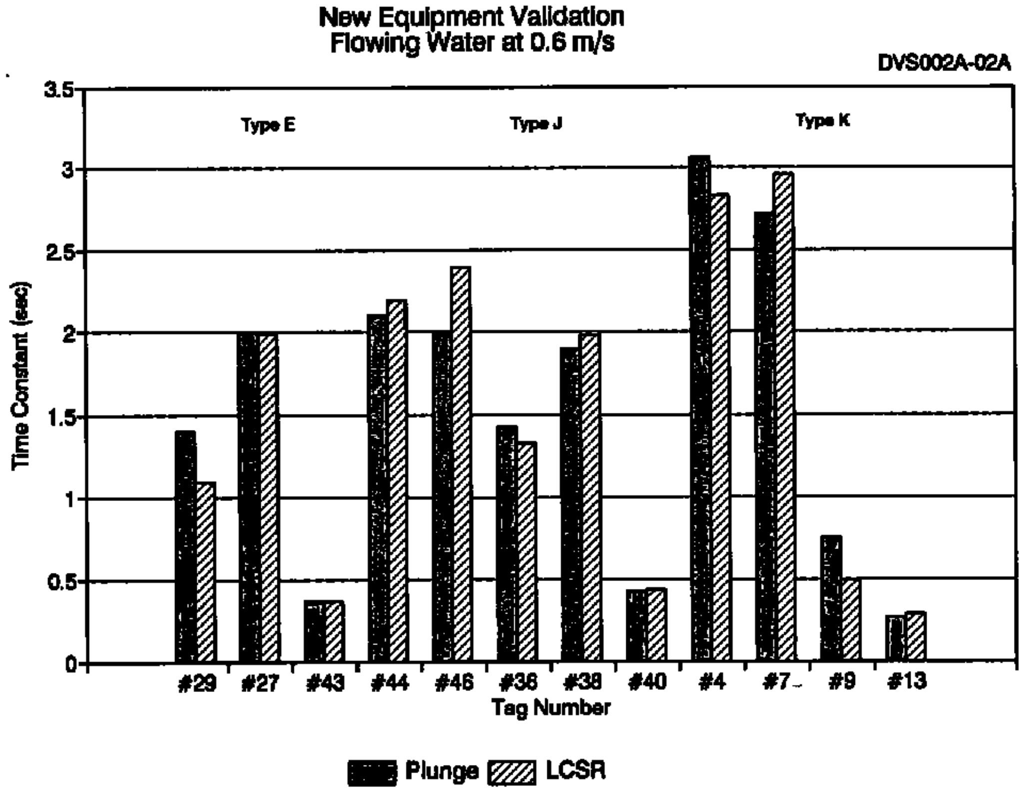


Figure 3.5.1. New Equipment Validation (0.6 m/s Water).

Table 3.6

**Manufactured Equipment Validation Results
(14 m/sec air)**

TC Tag #	Plunge Result (sec)	LCSR Result (sec)	|Difference| (sec)
40	3.20	3.63	0.43
38	9.90	9.48	0.42
52	1.28	1.54	0.26
13	3.66	7.03	3.37
09	10.03	14.68	4.65
07	17.13	18.27	1.14
51	1.12	1.10	0.02
43	3.88	3.90	0.02
29	10.55	8.61	1.94
27	17.10	19.45	2.35
20	0.16	0.10	0.06
18	0.14	0.12	0.02
23	0.50	0.56	0.06

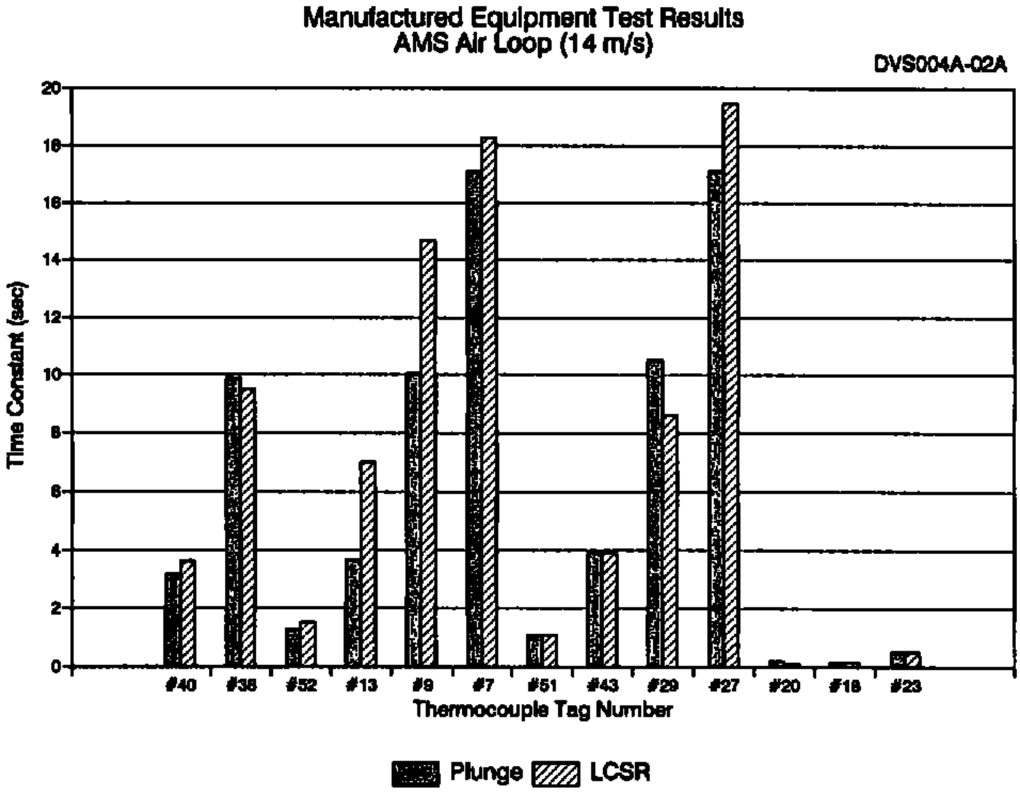


Figure 3.5.2. New Equipment Validation (14 m/s Air).

3.6 Problems Encountered During LCSR Testing

During the LCSR testing of thermocouples, various phenomena occurred which made data acquisition (and subsequent analysis) difficult. The LCSR data obtained for these cases were such that the averaging program could not adequately compensate for the problems. Examples of these are as follows:

1. Downward temperature drift (Figure 3.6.1). The transient displays a slow downward slope after having reached an initial plateau.
2. Upward temperature drift (Figure 3.6.2). The transient does not appear to reach a final value.
3. Spikes present during the initial portion of transient (Figure 3.6.3).
4. Electrical noise present in the thermocouple output (Figures 3.6.4 and 3.6.5).
5. Prompt jump in the initial portion of the transient (Figure 3.6.6).

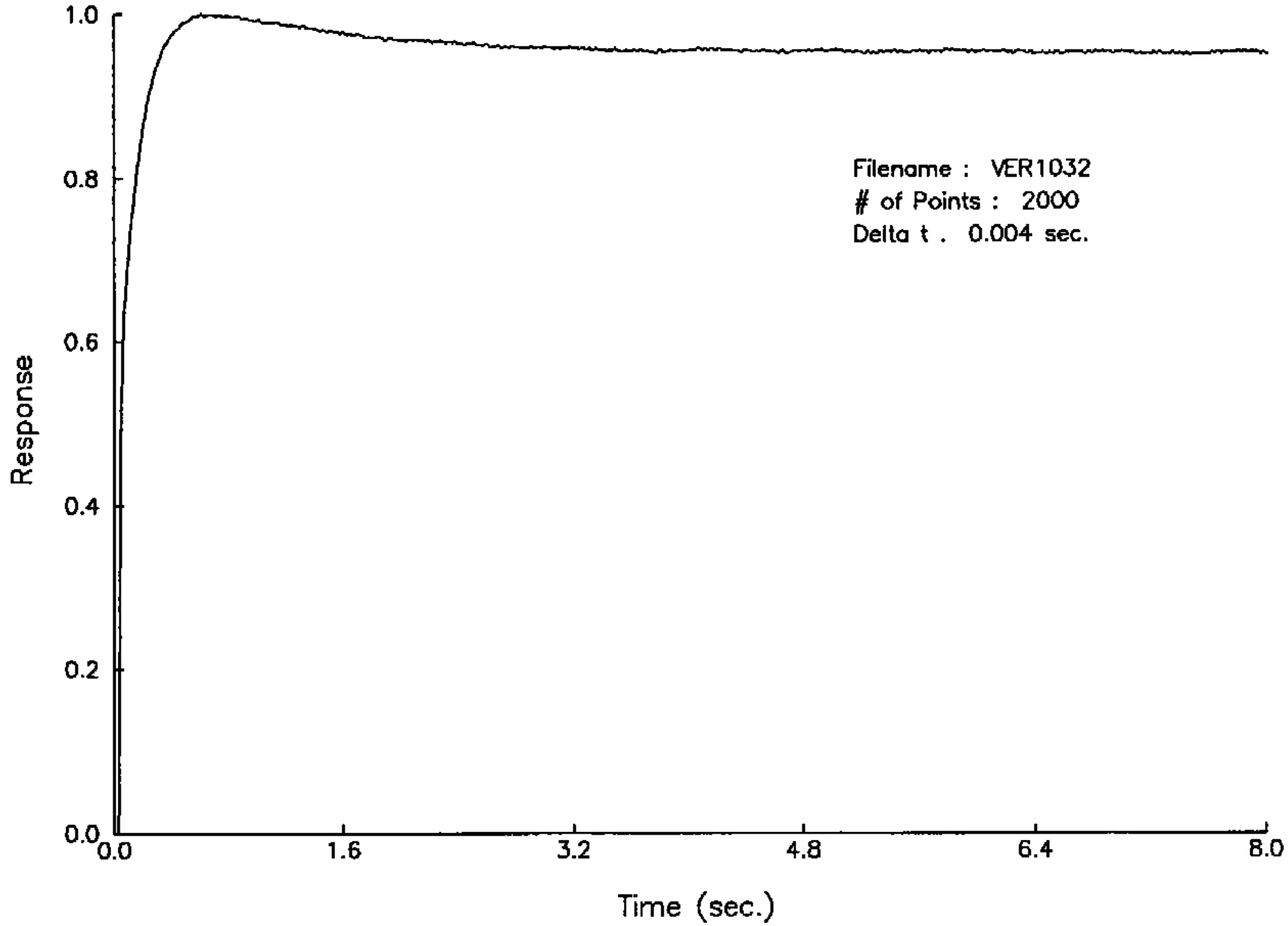


Figure 3.6.1. Averaged LCSR Transient for Sensor Tag No. AF #46 (Downward Drift) .

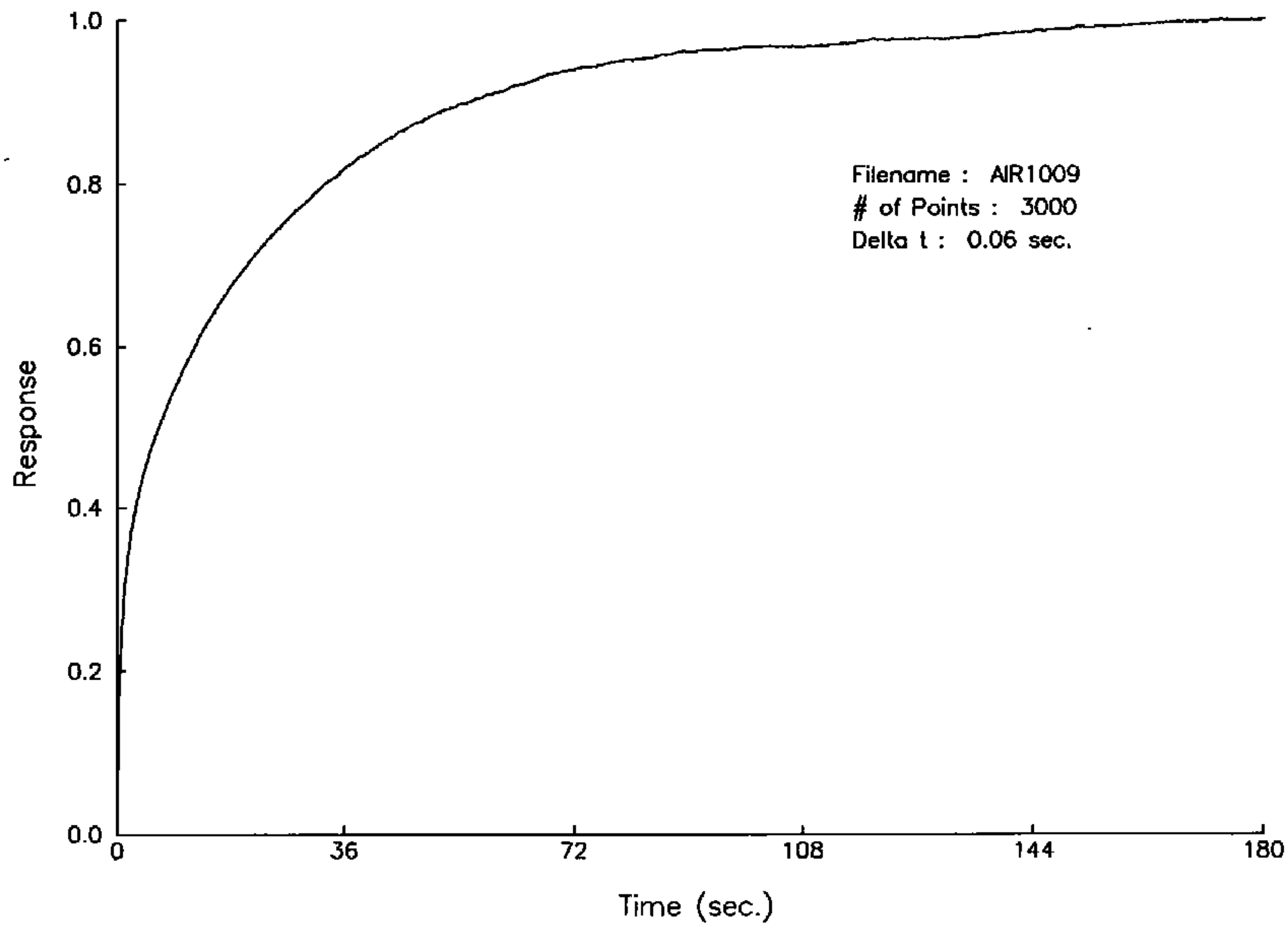


Figure 3.6.2. Averaged LCSR Transient for Sensor Tag No. AF #44 (Upward Drift).

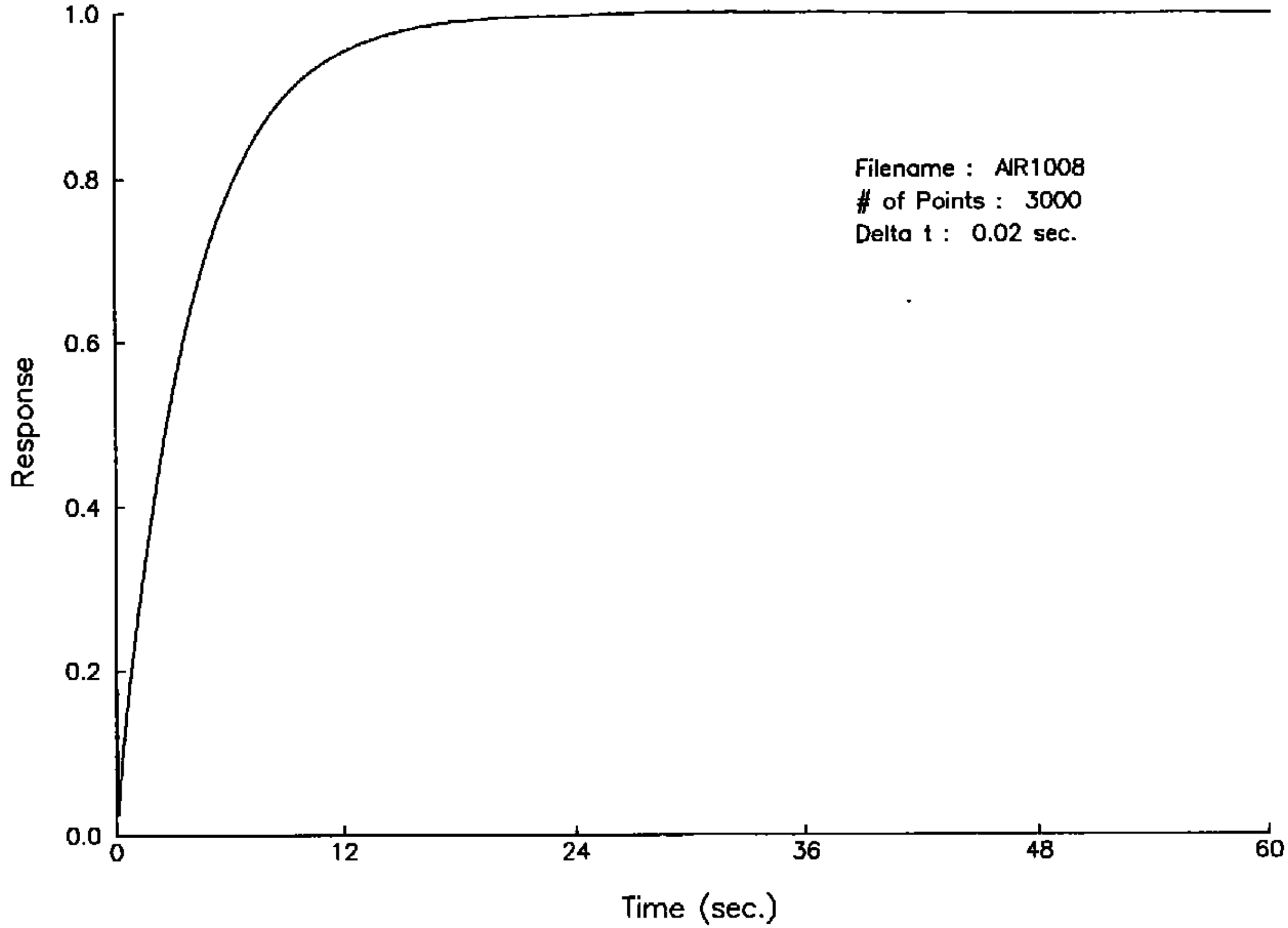


Figure 3.6.3. Averaged LCSR Transient for Sensor Tag No. AF #13 (Spikes in Transient) .

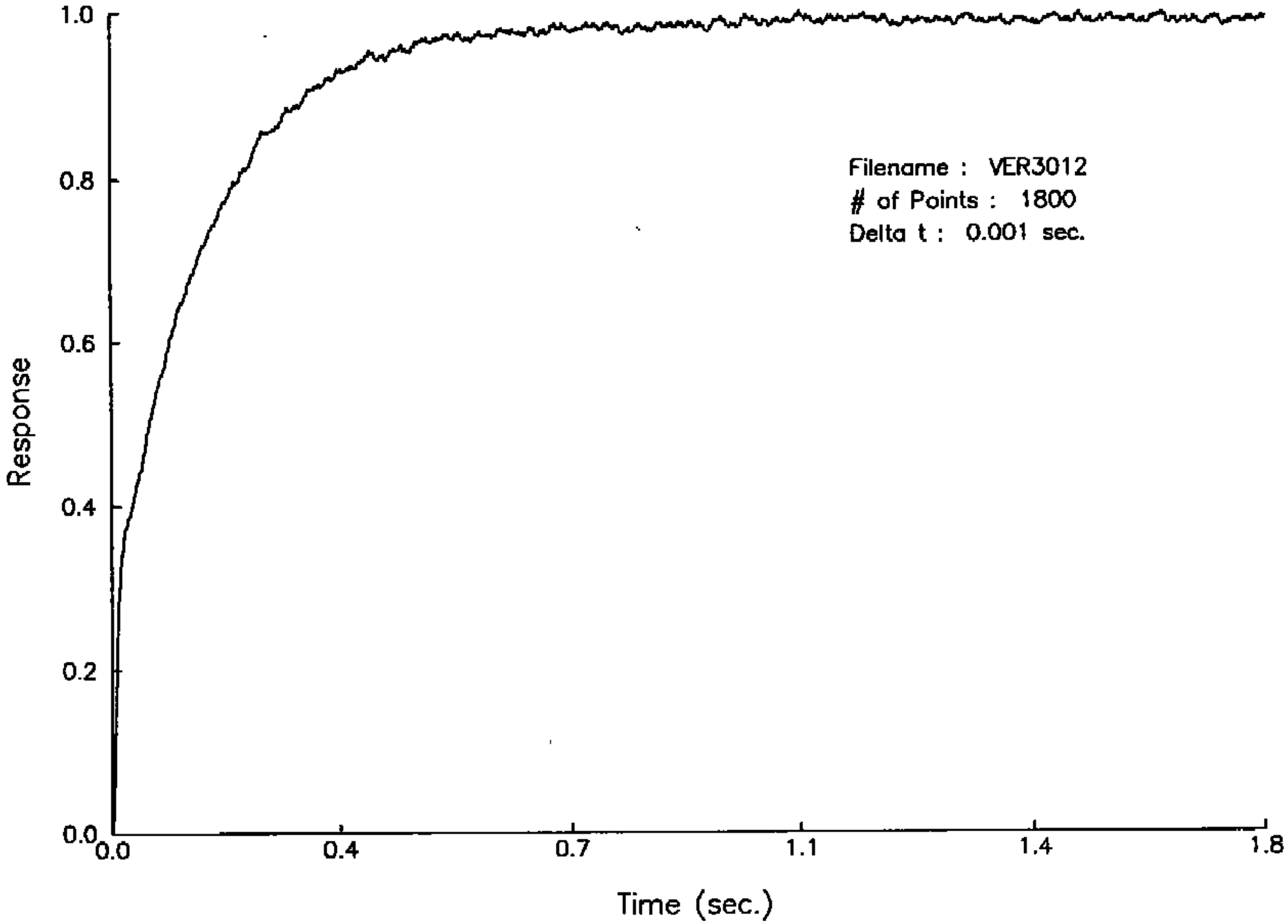


Figure 3.6.4. Averaged LCSR Transient for Sensor Tag No. AF #13 (Noise in Transient) .

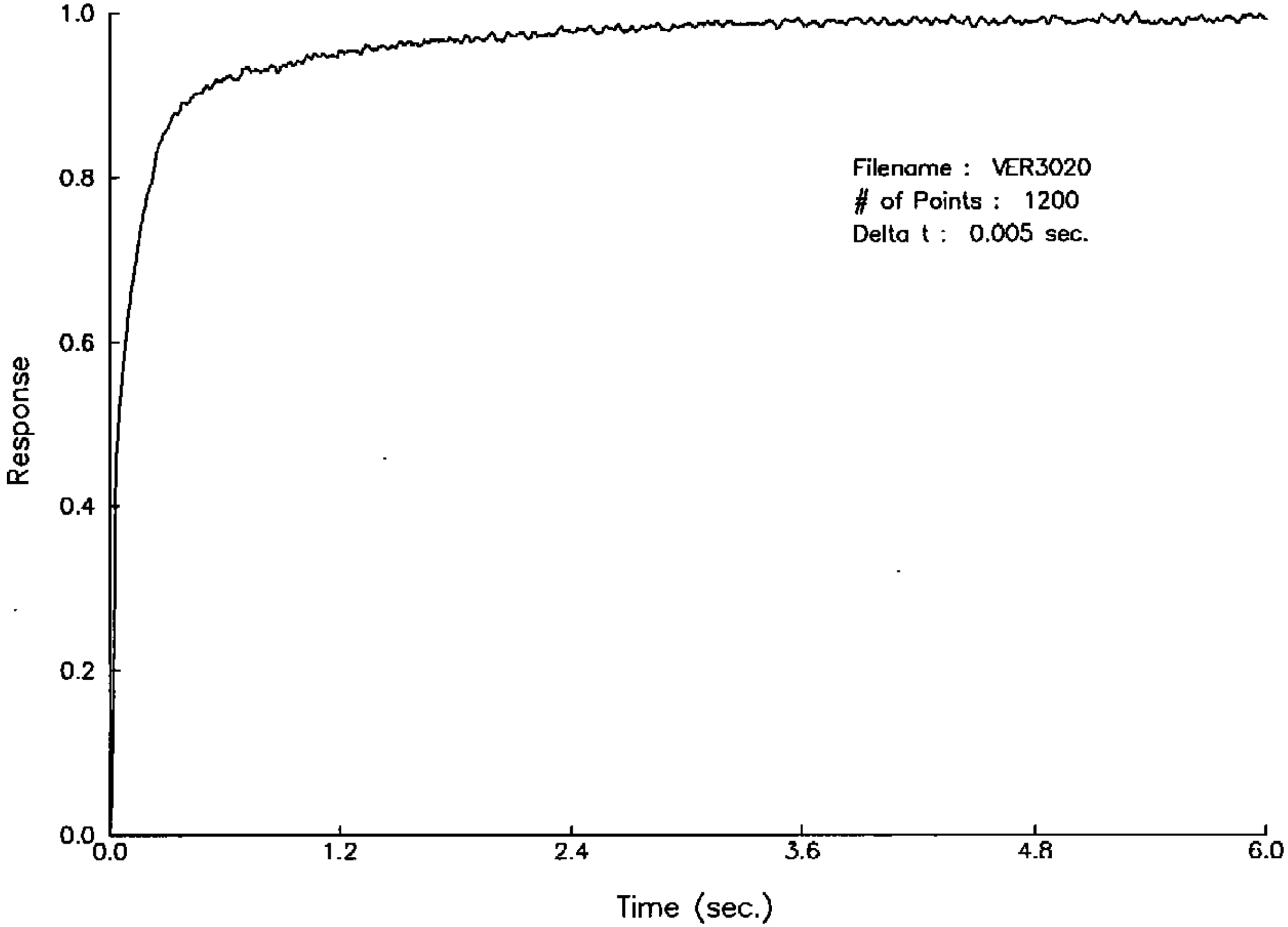


Figure 3.6.5. Averaged LCSR Transient for Sensor Tag No. AF #36 (Noise in Transient) .

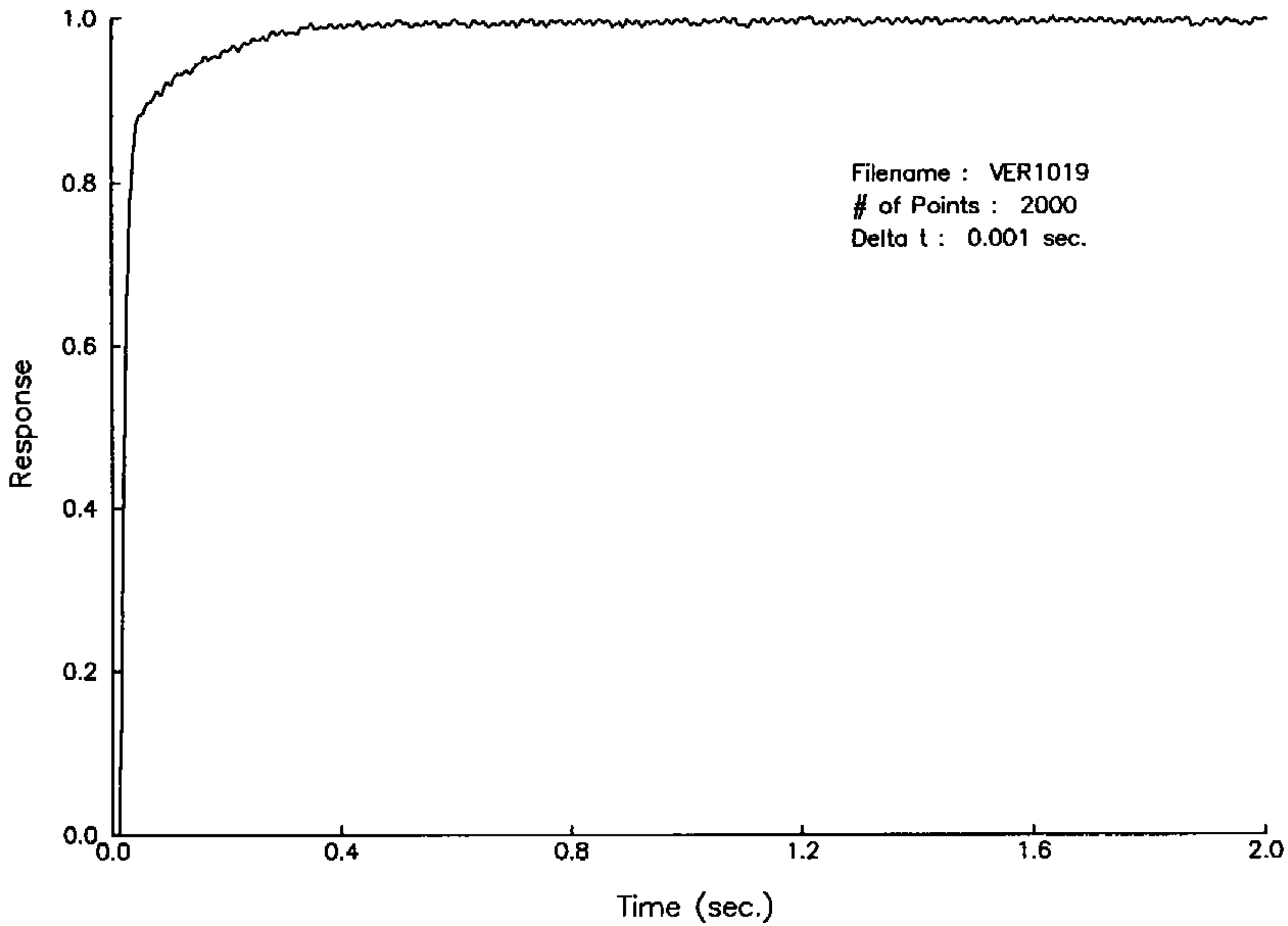


Figure 3.6.6. Averaged LCSR Transient for Sensor Tag No. AF #32 (Prompt Jump).

4. EFFECTS OF APPLIED CURRENT AND HEATING TIME ON LCSR

The identification of baseline values to use for the various LCSR test parameters is required to obtain accurate response time results. The amount of electrical current used to heat a thermocouple and heating time duration are two parameters which can be varied during LCSR testing to accomplish this.

To quantify how these two parameters affect LCSR testing of thermocouples, a series of tests was performed on 11 thermocouples of different sizes and types. The tests were performed by systematically changing both parameters such that the effects of each on LCSR results could be evaluated. The heating times used during these tests were 5 and 15 seconds. The currents used were 0.25, 0.5 and 1.0 amperes for thermocouples with 23, 24, and 30 gage wires; 0.75, 1.0 and 1.5 amperes for thermocouples with 18 and 20 gage wire. Other parameters (number of points sampled and sampling rate) were varied according to each thermocouple's response to the test conditions. LCSR results were compared to baseline plunge test results to evaluate the effect of the test.

The results of this work are shown in Table 4.1. Composite graphs describing this data are shown for the following cases in terms of differences between the plunge and LCSR results. (These differences can be converted to percent differences using the nominal response times of the thermocouple from plunge test results shown earlier):

1. Differences in response time versus heating current for thermocouples tested with a 5 second heating time (Figure 4.1).

2. Individual thermocouple response time differences for 5 second heating times (Figures 4.2 through 4.4). These graphs are intended to indicate that the response time differences may increase, decrease or remain relatively stable as current is varied.

3. Differences in response times versus heating currents for thermocouples tested with a 15 second heating time (Figure 4.5).

TABLE 4.1

Effects of Heating Time and Current (0.6 m/s Water)

Effect of Heating Time and Current (2 FPS Water)
JJG006A.WQ1

Tag Number	Type	Heating Current (Amps)	Heating Time (Seconds)	Tau Corrected (Seconds)	Plunge (Seconds)	Difference (Seconds)	Wire Gage	Outside Dia. (mm)	Loop Res. (Ohms)
4	K Quick	0.75	5	2.2	3.06	0.86	18	6	0.65
4	K Quick	0.75	15	2.9	3.06	0.16	18	6	0.65
4	K Quick	1	5	2.3	3.06	0.76	18	6	0.65
4	K Quick	1	15	2.8	3.06	0.26	18	6	0.65
4	K Quick	1.5	5	2.3	3.06	0.76	18	6	0.65
4	K Quick	1.5	15	2.9	3.06	0.16	18	6	0.65
7	K Quick	0.75	5	2.3	2.75	0.45	20	5	0.66
7	K Quick	0.75	15	2.6	2.72	0.12	20	5	0.66
7	K Quick	1	5	2.2	2.72	0.52	20	5	0.66
7	K Quick	1	15	2.4	2.72	0.32	20	5	0.66
7	K Quick	1.5	5	2.3	2.72	0.42	20	5	0.66
7	K Quick	1.5	15	2.4	2.72	0.32	20	5	0.66
9	K Quick	0.25	5	0.2	0.76	0.56	23	3	1.46
9	K Quick	0.25	15	0.2	0.76	0.56	23	3	1.46
9	K Quick	0.5	5	0.5	0.76	0.26	23	3	1.46
9	K Quick	0.5	15	0.5	0.76	0.26	23	3	1.46
9	K Quick	1	5	0.4	0.76	0.36	23	3	1.46
9	K Quick	1	15	0.5	0.76	0.26	23	3	1.46
27	E Quick	0.75	5	2.4	2	-0.40	20	5	0.79
27	E Quick	0.75	15	1.8	2	0.20	20	5	0.79
27	E Quick	1	5	2	2	0.00	20	5	0.79
27	E Quick	1	15	2.2	2	-0.20	20	5	0.79
27	E Quick	1.5	5	1.6	2	0.40	20	5	0.79
27	E Quick	1.5	15	1.7	2	0.30	20	5	0.79
29	E Quick	0.25	5	2	1.4	-0.60	23	3	1.57
29	E Quick	0.25	15	1.5	1.4	-0.10	23	3	1.57
29	E Quick	0.5	5	1.1	1.4	0.30	23	3	1.57
29	E Quick	0.5	15	1	1.4	0.40	23	3	1.57
29	E Quick	1	5	1.1	1.4	0.30	23	3	1.57
29	E Quick	1	15	1.3	1.4	0.10	23	3	1.57
36	J Trans 29"	0.75	5	1.4	1.43	0.03	20	5	1.47
36	J Trans 29"	0.75	15	1	1.43	0.43	20	5	1.47
36	J Trans 29"	1	5	1.3	1.43	0.13	20	5	1.47
36	J Trans 29"	1	15	1.4	1.43	0.03	20	5	1.47
36	J Trans 29"	1.5	5	1	1.43	0.43	20	5	1.47
36	J Trans 29"	1.5	15	1	1.43	0.43	20	5	1.47
38	J Quick	0.25	5	1.7	1.9	0.20	24	3	1.26
38	J Quick	0.25	15	1.8	1.9	0.10	24	3	1.26
38	J Quick	0.5	5	1.4	1.9	0.50	24	3	1.26
38	J Quick	0.5	15	1.4	1.9	0.50	24	3	1.26
38	J Quick	1	5	1.5	1.9	0.40	24	3	1.26
38	J Quick	1	15	1.6	1.9	0.30	24	3	1.26
40	J Quick	0.25	5	0.23	0.43	0.20	30	2	3.29
40	J Quick	0.25	15	0.26	0.43	0.17	30	2	3.29
40	J Quick	0.5	5	0.3	0.43	0.13	30	2	3.29
40	J Quick	0.5	15	0.3	0.43	0.13	30	2	3.29
40	J Quick	1	5	0.42	0.43	0.01	30	2	3.29
40	J Quick	1	15	0.33	0.43	0.10	30	2	3.29
43	E Quick	0.25	5	0.22	0.37	0.15	30	2	6.9
43	E Quick	0.25	15	0.27	0.37	0.10	30	2	6.9
43	E Quick	0.5	5	0.29	0.37	0.08	30	2	6.9
43	E Quick	0.5	15	0.26	0.37	0.11	30	2	6.9
43	E Quick	1	5	0.29	0.37	0.08	30	2	6.9
43	E Quick	1	15	0.29	0.37	0.08	30	2	6.9
44	E Quick	0.75	5	1.9	2.1	0.20	18	6	0.85
44	E Quick	0.75	15	2.1	2.1	0.00	18	6	0.85
44	E Quick	1	5	2.1	2.1	0.00	18	6	0.85
44	E Quick	1	15	2.1	2.1	0.00	18	6	0.85
44	E Quick	1.5	5	2.4	2.1	-0.30	18	6	0.85
44	E Quick	1.5	15	2	2.1	0.10	18	6	0.85
46	J Quick	0.75	5	2.3	1.98	-0.32	18	6	0.6
46	J Quick	0.75	15	2.2	1.98	-0.22	18	6	0.6
46	J Quick	1	5	2.1	1.98	-0.12	18	6	0.6
46	J Quick	1	15	1.8	1.98	0.18	18	6	0.6
46	J Quick	1.5	5	1.7	1.98	0.28	18	6	0.6
46	J Quick	1.5	15	1.9	1.98	0.08	18	6	0.6

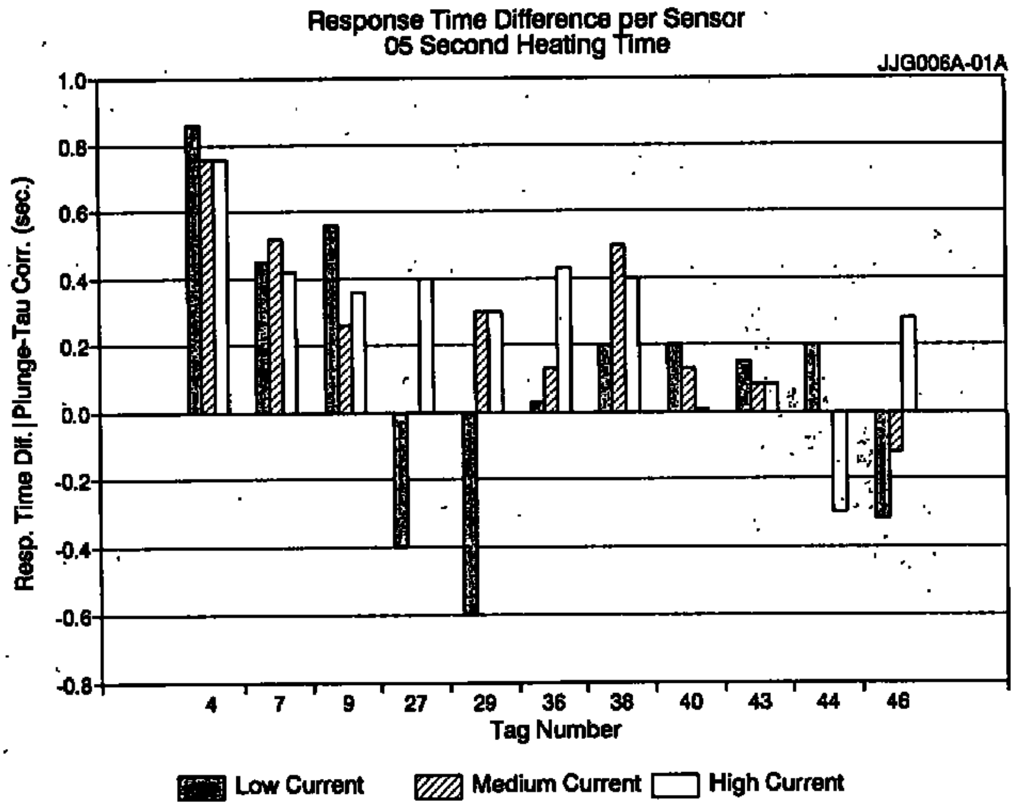


Figure 4.1. Composite Graph of Thermocouples Tested with 5 Second Heating Times.

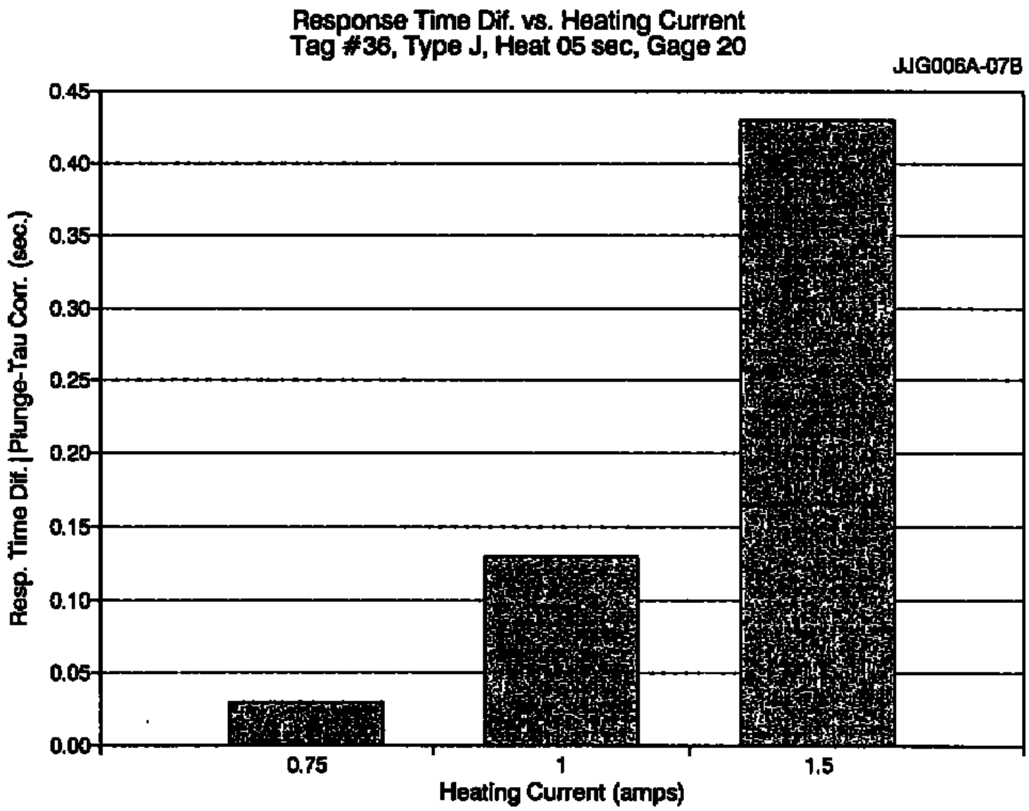


Figure 4.2. Example of Thermocouple with Increasing Errors as Current was Increased. (AF#36, 5 Second Heating Time.)

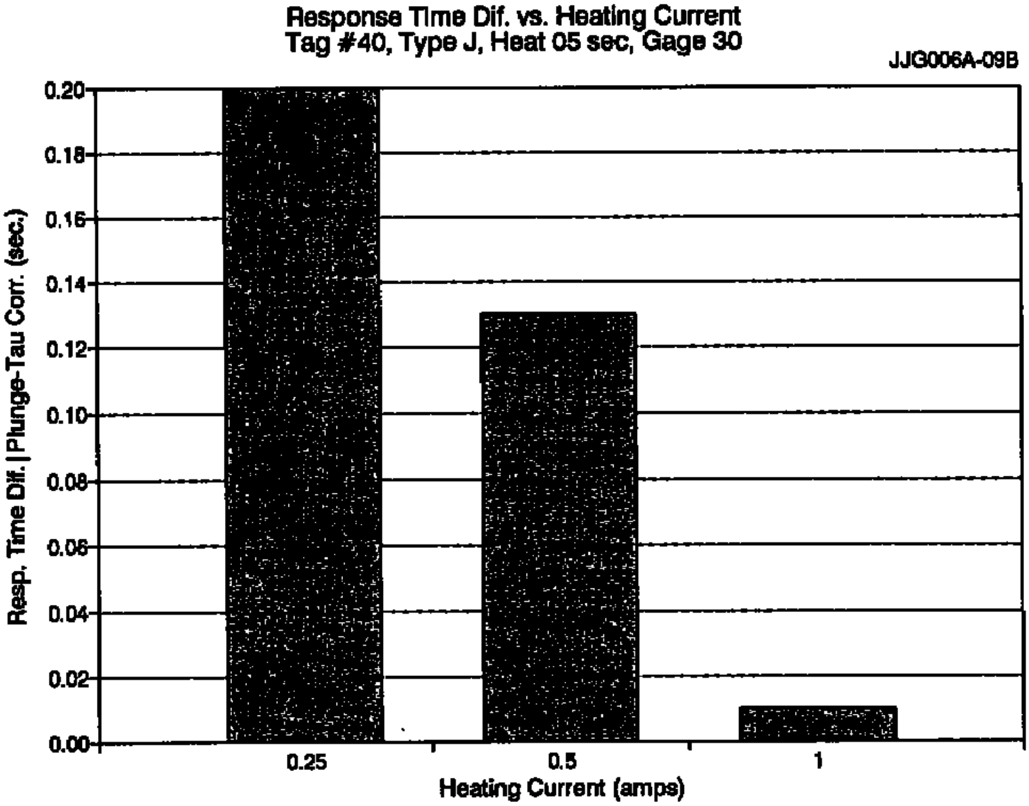


Figure 4.3. Example of Thermocouple with Decreasing Errors as Current was Increased. (AF#40, 5 Second Heating Time.)

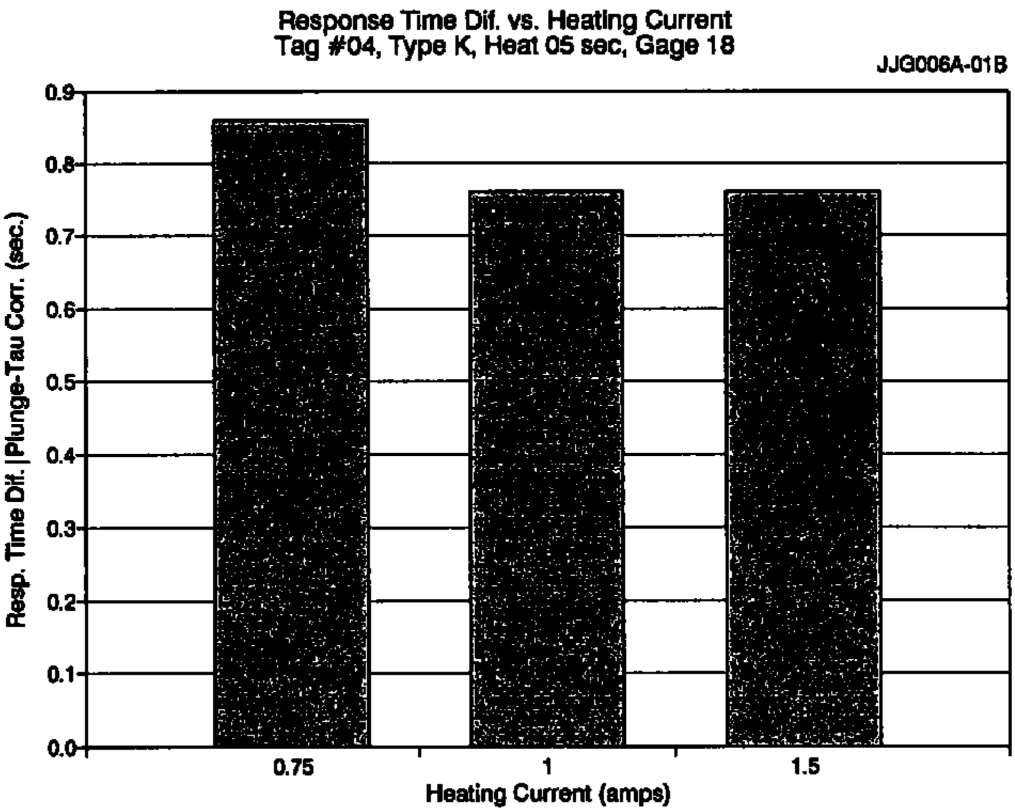


Figure 4.4. Example of Thermocouple with Relatively Constant Errors as Current was Increased. (AF#04, 5 Second Heating Time.)

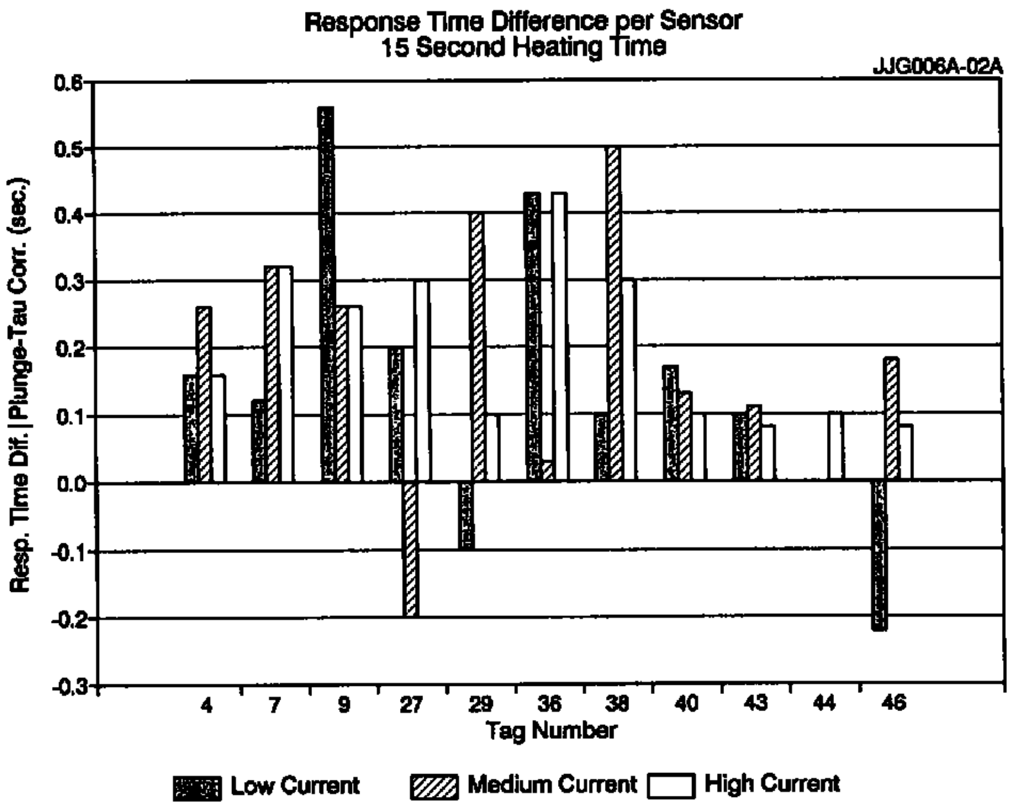


Figure 4.5. Composite Graph of Thermocouples Tested with 15 Second Heating Times.

4. Individual thermocouple response time differences for 15 second heating times (Figures 4.6 through 4.8). These graphs again illustrate that the response time differences may vary or remain stable as current is changed.

5. Differences in response times for various thermocouples tested with 5 and 15 second heating times (Figures 4.9 through 4.13). These figures are shown to illustrate the effects of different heating times on the response of the thermocouple.

6. Example LCSR transients of a specific thermocouple using low, medium, and high currents (Figures 4.14 through 4.16). The currents used were 0.25, 0.50, and 1.0 ampere respectively.

7. Example LCSR transients for a thermocouple using high current and varied heating times (Figures 4.17 and 4.18). The current used was 1.0 ampere.

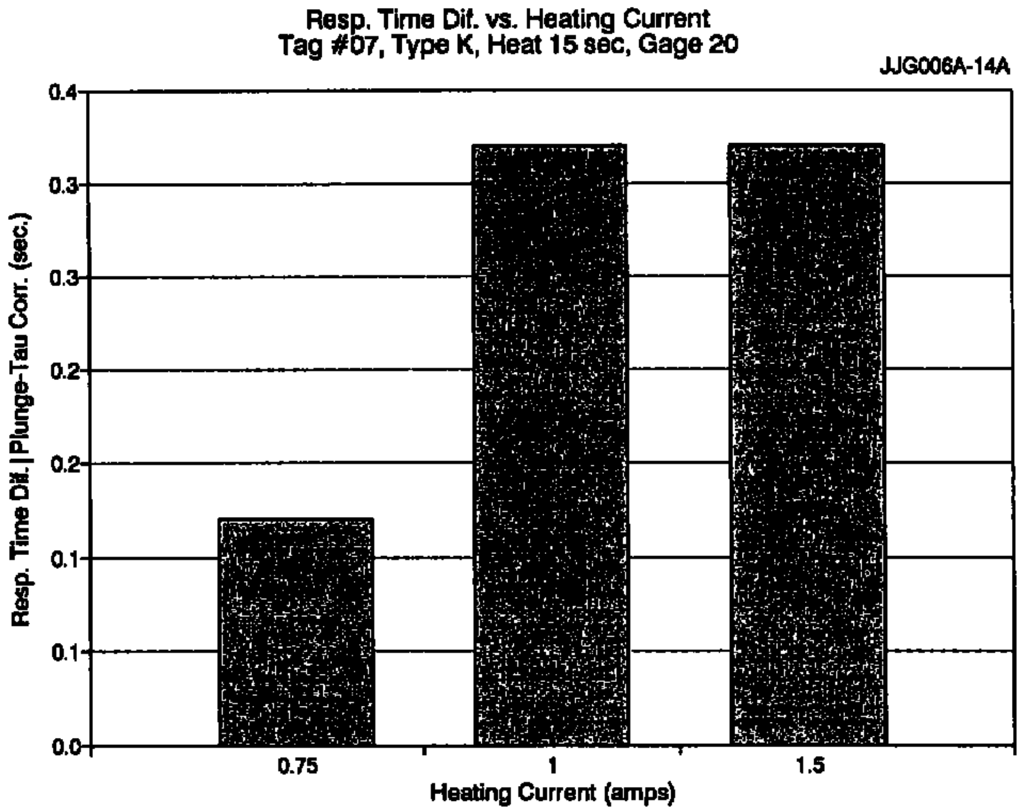


Figure 4.6. Example of Thermocouple with Increasing Errors as Current was Increased. (AF#07, 15 Second Heating Time.)

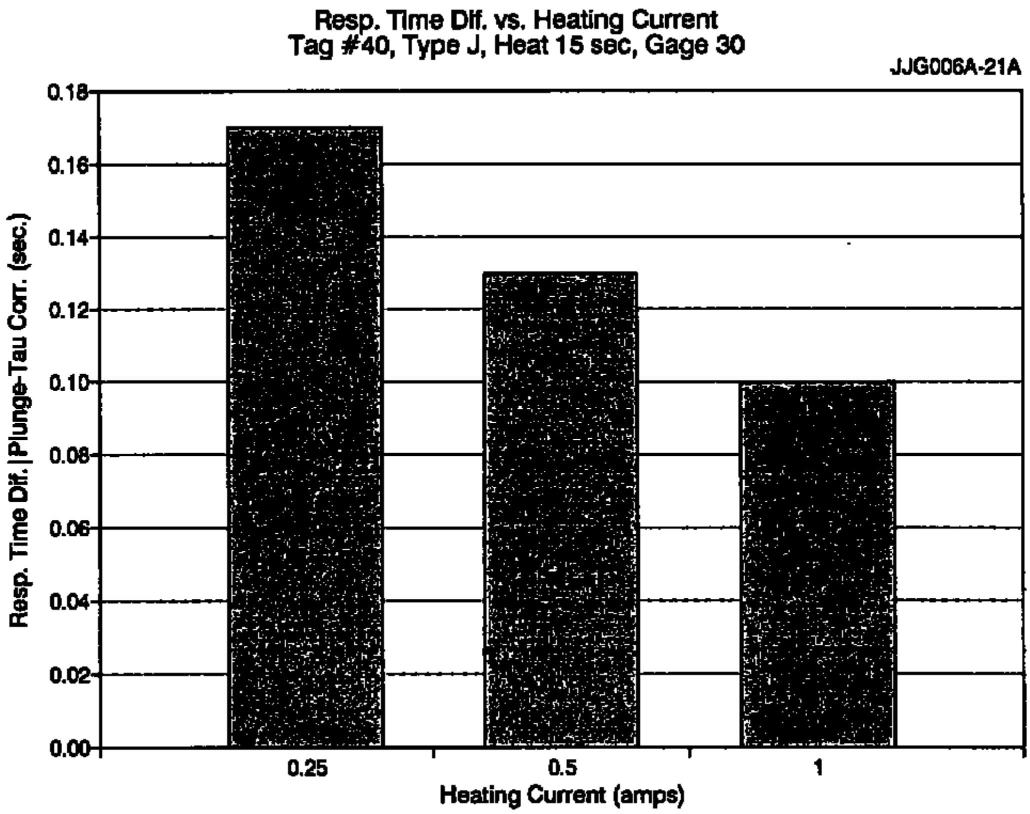


Figure 4.7. Example of Thermocouple with Decreasing Errors as Current was Increased. (AF#40, 15 Second Heating Time.)

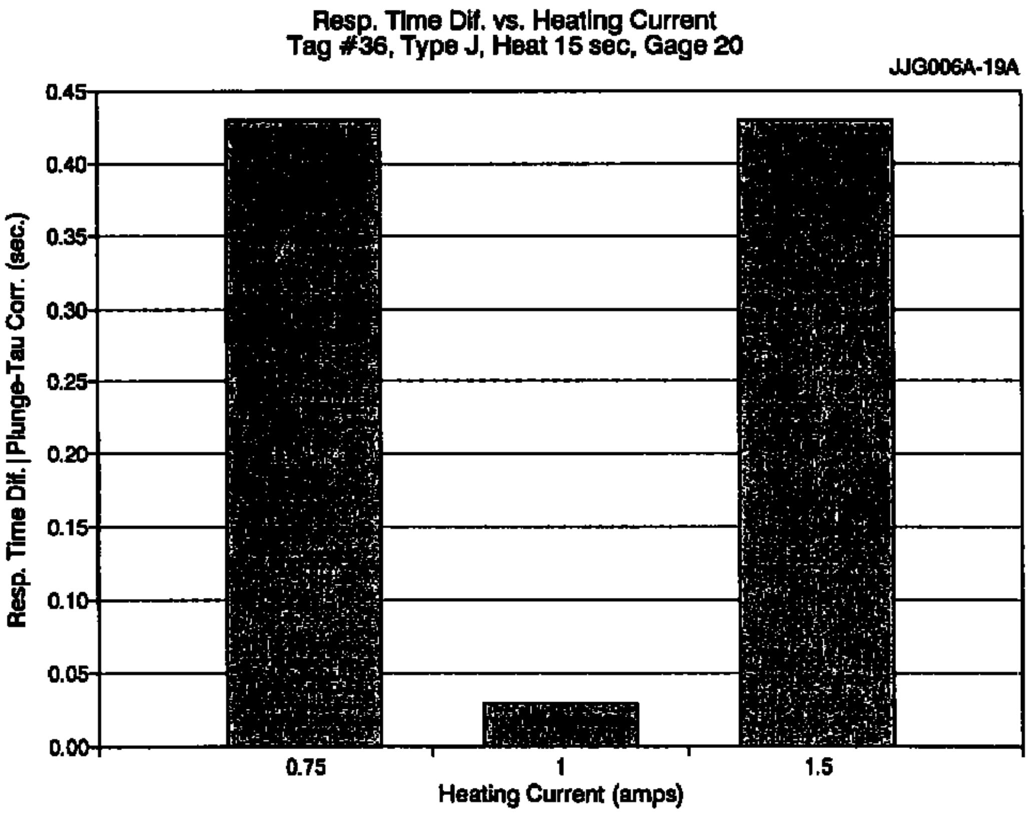


Figure 4.8. Example of Thermocouple with Relatively Constant Errors as Current was Increased. (AF#36, 15 Second Heating Time.)

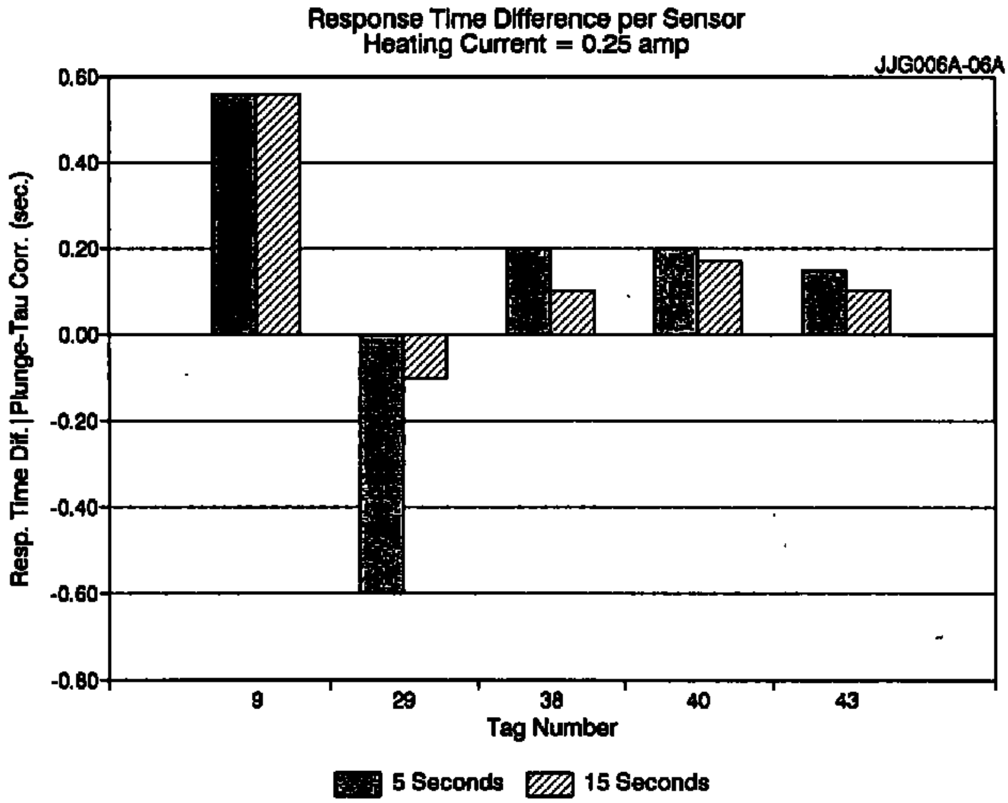


Figure 4.9. Response Time Differences Using 0.25A (5/15 Second Heating Times).

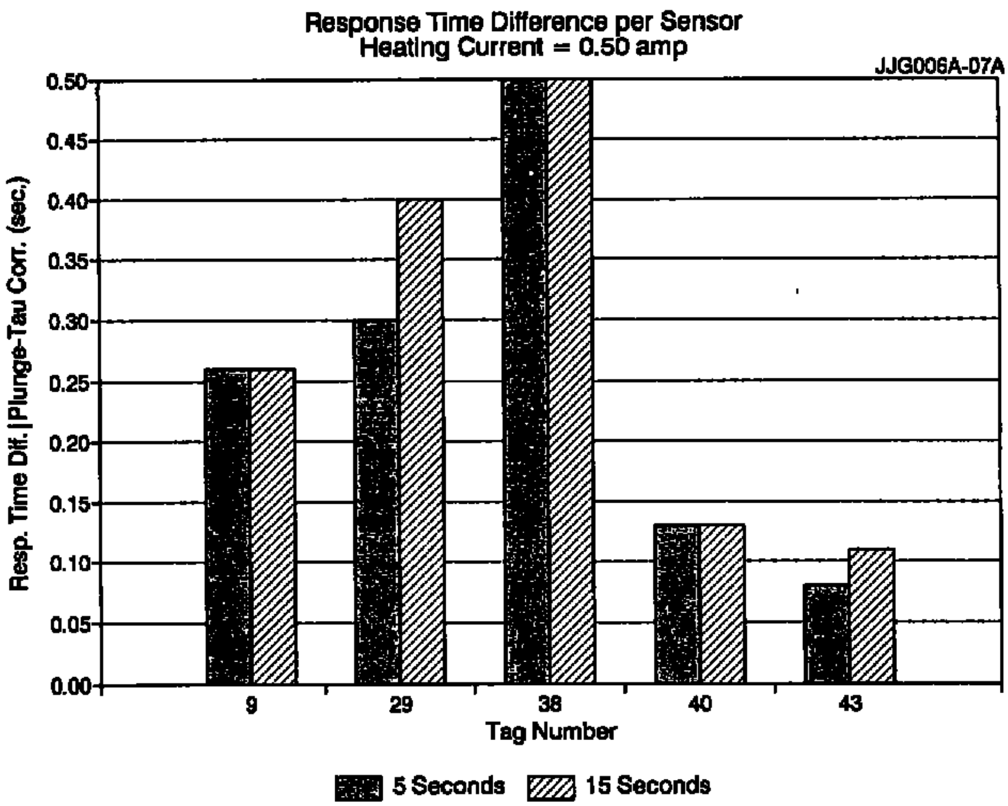


Figure 4.10. Response Time Differences Using 0.5A (5/15 Second Heating Times).

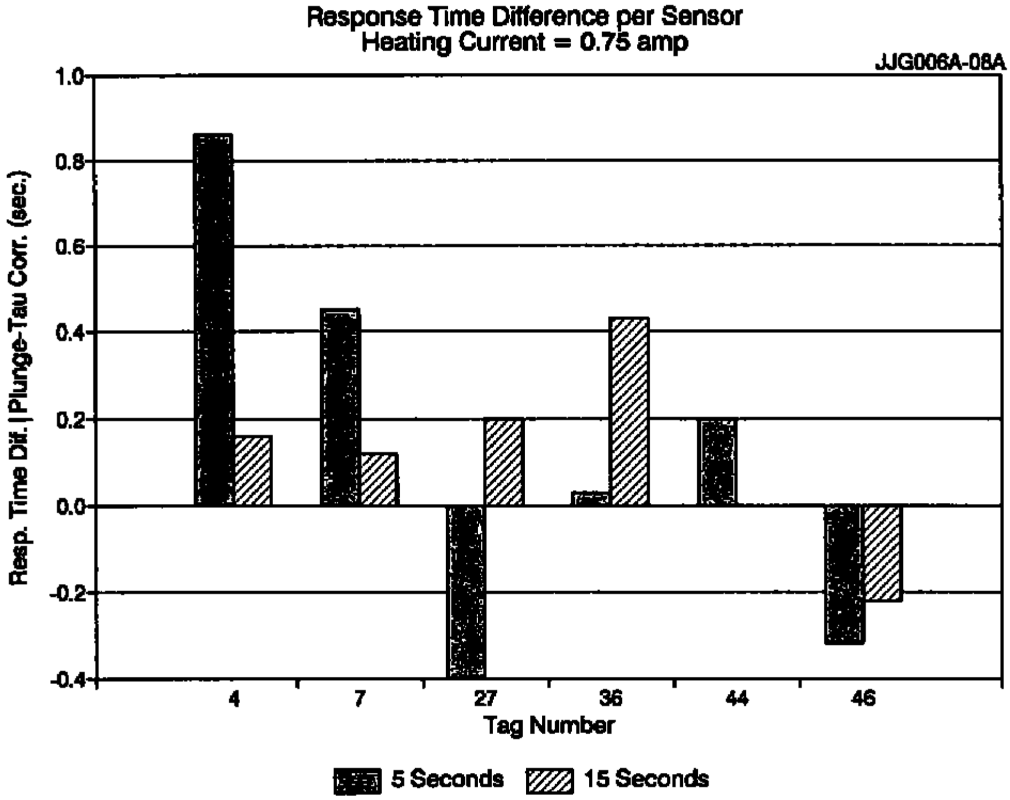


Figure 4.11. Response Time Differences Using 0.75A (5/15 Second Heating Times)

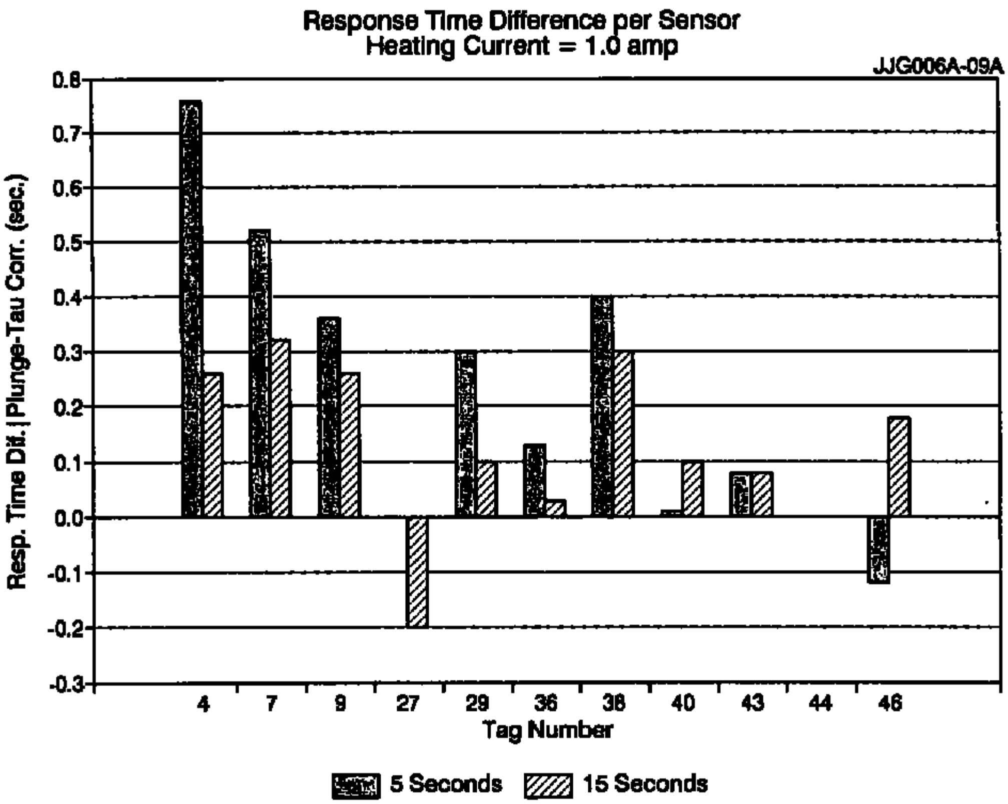


Figure 4.12. Response Time Differences Using 1.0A (5/15 Second Heating Times).

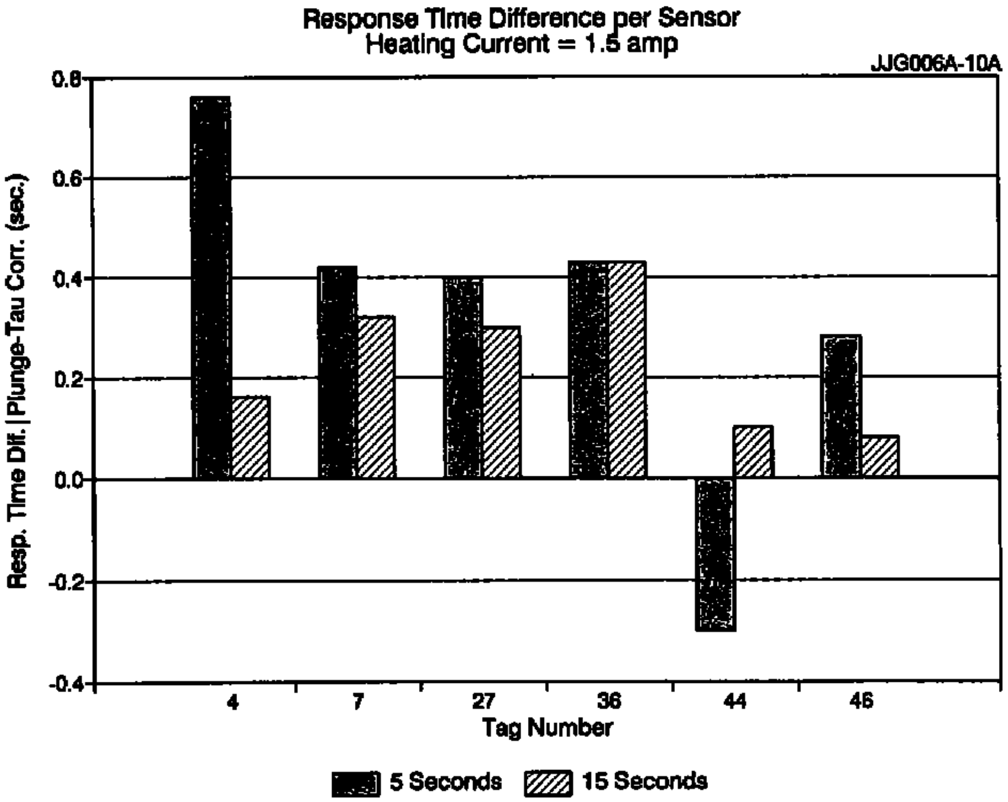


Figure 4.13. Response Time Differences Using 1.5A (5/15 Second Heating Times).

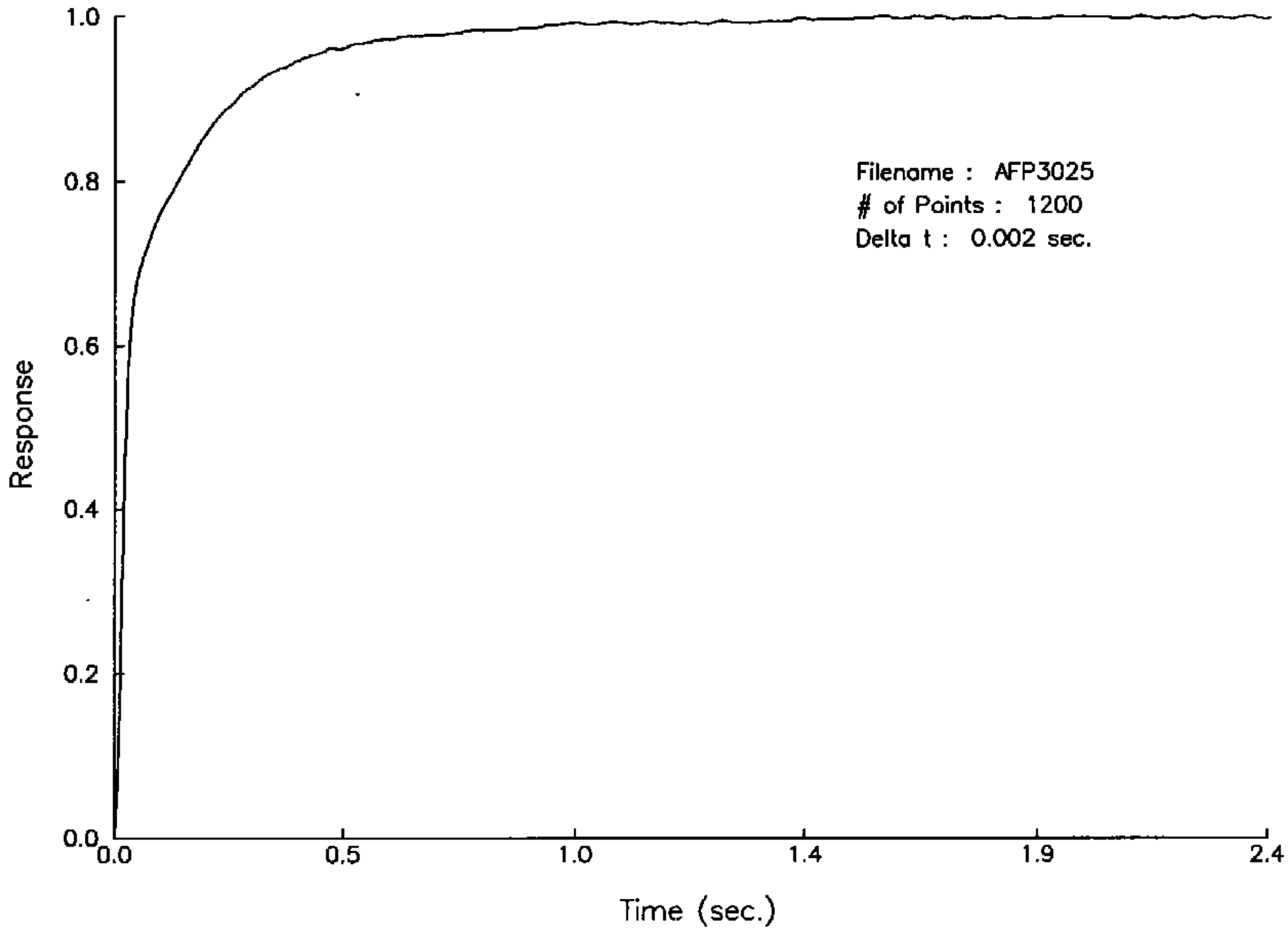


Figure 4.14. Averaged LCSR Transient for Sensor Tag No. AF #43 (0.25A, 5 sec Heating) .

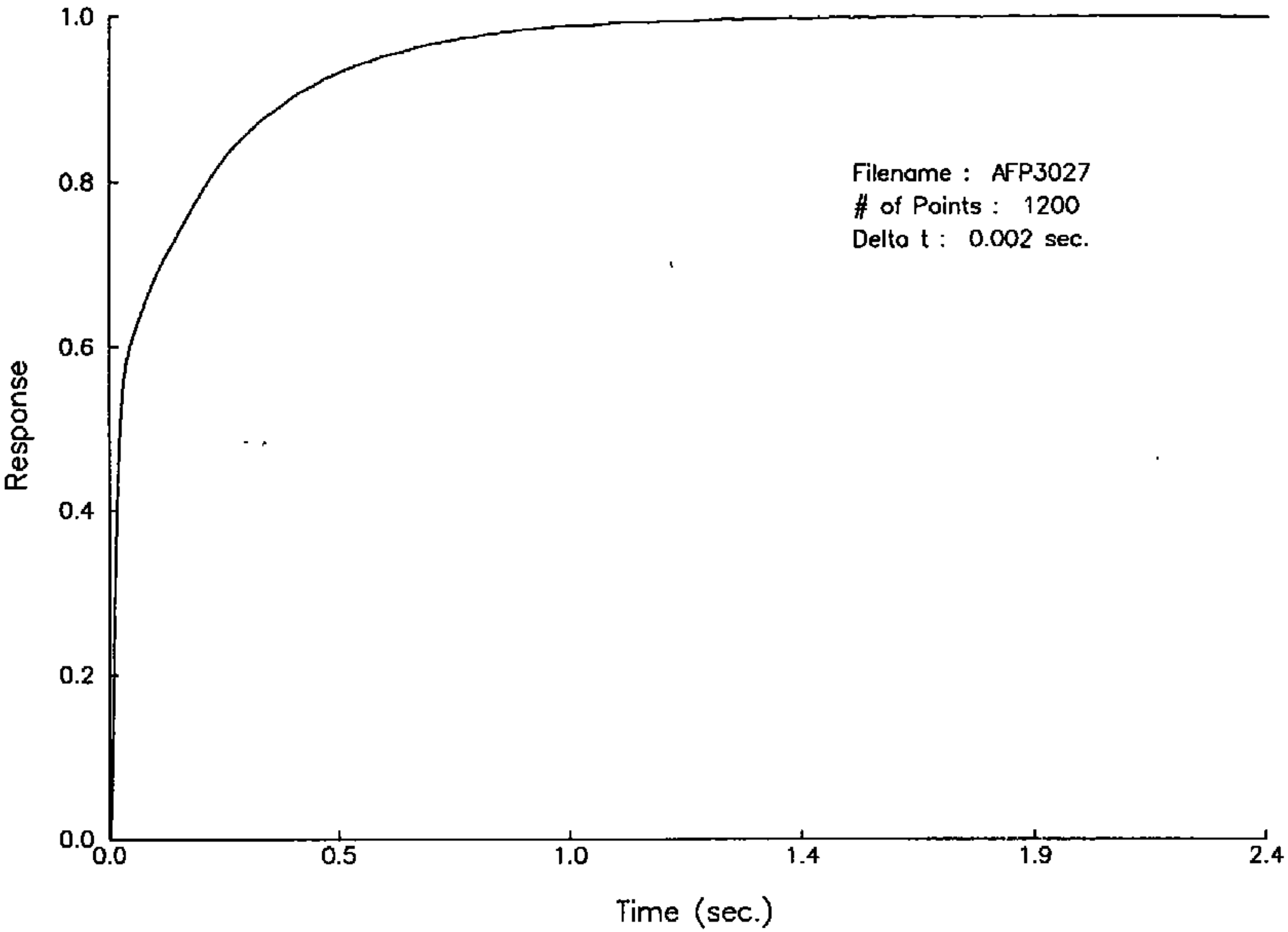


Figure 4.15. Averaged LCSR Transient for Sensor Tag No. AF #43 (0.5A, 5 sec Heating) .

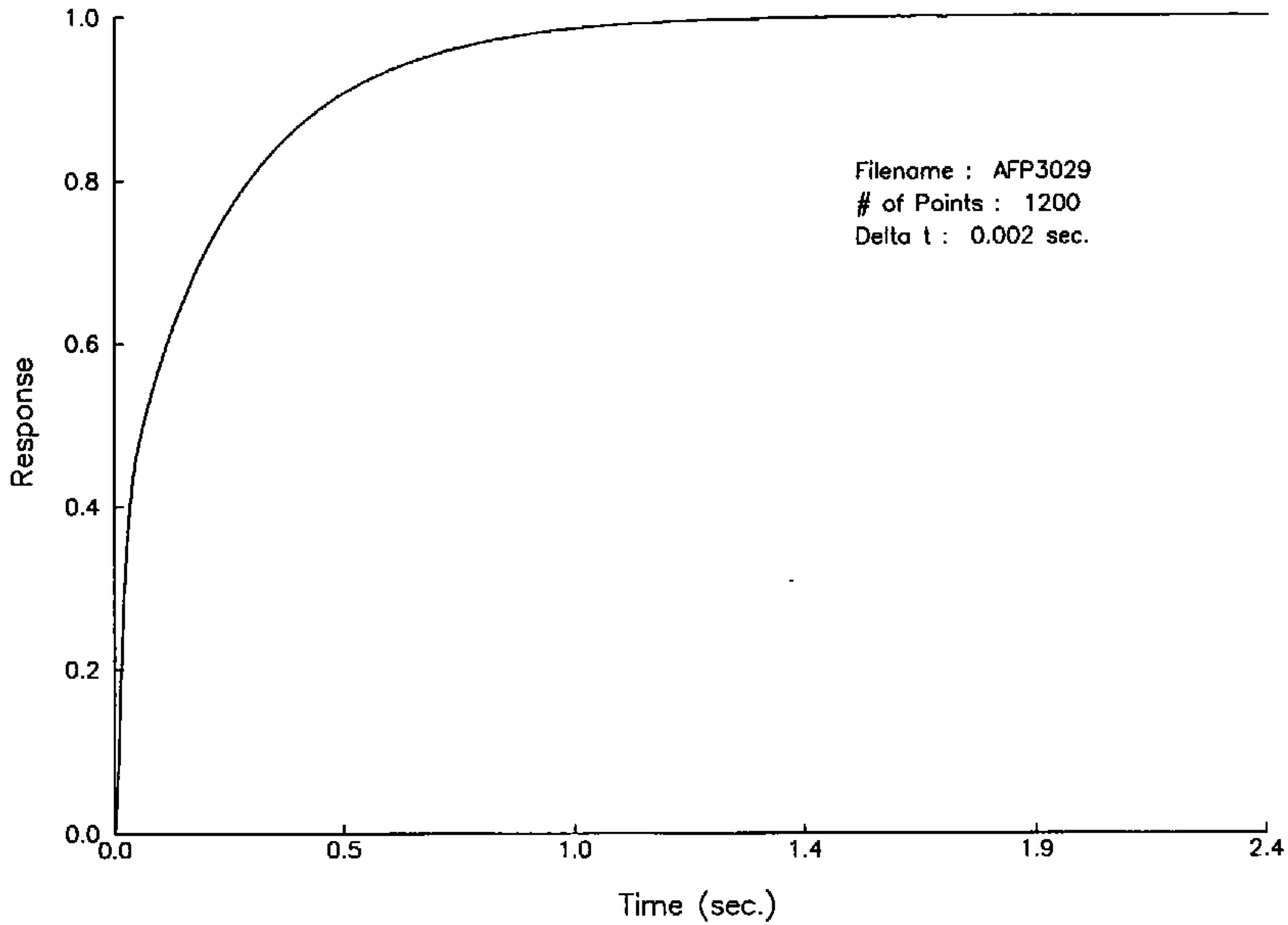


Figure 4.16. Averaged LCSR Transient for Sensor Tag No. AF #43 (1.0A, 5 sec Heating) .

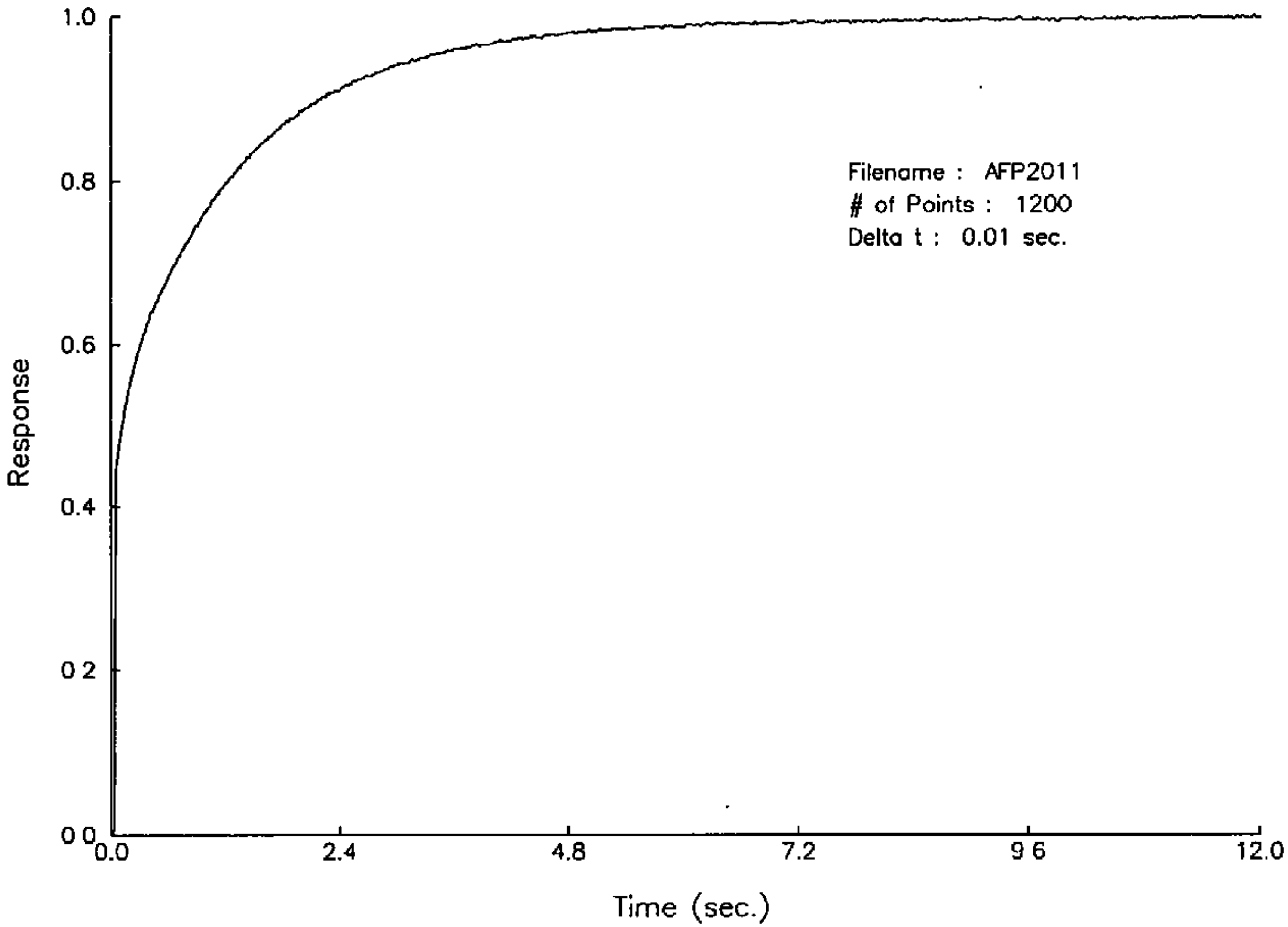


Figure 4.17. Averaged LCSR Transient for Sensor Tag No. AF #38 (1.0A, 5 sec Heating) .

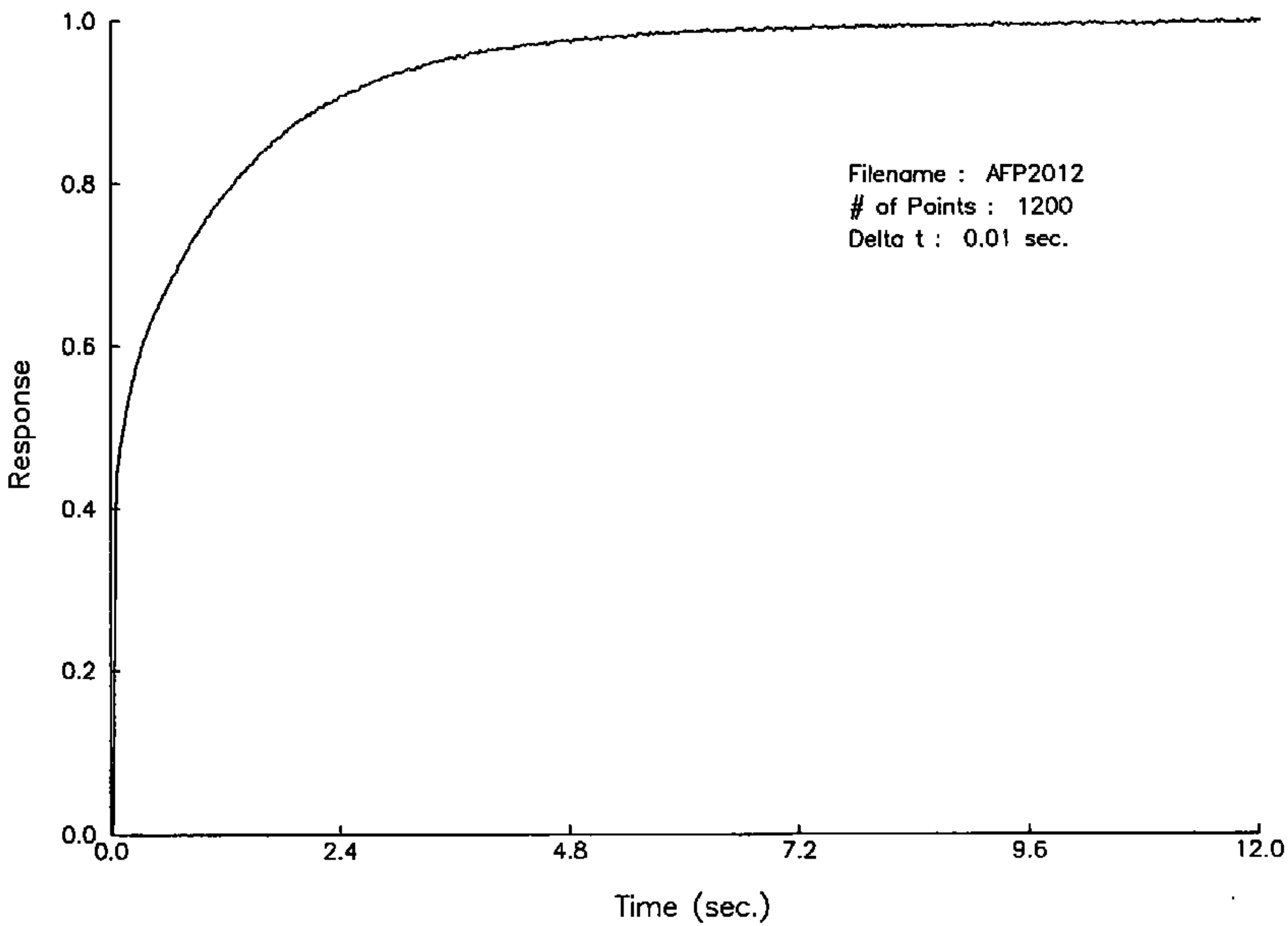


Figure 4.18. Averaged LCSR Transient for Sensor Tag No. AF #38 (1.0A, 15 sec Heating) .

5. EFFECTS OF EXTENSION WIRE LENGTH ON LCSR FOR THERMOCOUPLES

Many of the research and industry applications in which thermocouples are used require long extension wires from the thermocouple to the monitoring/measuring equipment. To verify that the LCSR method could be used for response time testing of thermocouples with long extension wires, a series of systematic tests were performed.

The tests involved the selection of several thermocouples of varied size and type and the use of three different extension wire lengths (6 m (≈20'), 9 m (≈30') and 15 m (≈50')). All of the extension wires were 20 gage solid wires, except in the case of one 6 m length (type "K") stranded wire which was also used to study the effects of wire type on LCSR test results. All of the tests were performed in both water and air using 1.5 amperes of current applied for 15 seconds. The subsequent LCSR results were compared to baseline plunge test results.

5.1 Effects in Water

For the tests performed in water, 6 thermocouples and 0.6 m/sec flow were used. Table 5.1 shows the results of this testing. Graphs and plots further describing this data are shown for the following cases:

1. Composite graph of all the thermocouples tested showing differences between plunge and LCSR results as the extension wire lengths were changed (Figure 5.1.1).
2. Differences between plunge and LCSR test results for each thermocouple and wire length (Figure 5.1.2).
3. Individual thermocouple response time differences as wire lengths were changed (Figures 5.1.3 through 5.1.8). These plots reflect how each specific thermocouple responded to different extension wire lengths.
4. Sample LCSR transients for a typical thermocouple as extension wire lengths were changed (Figures 5.1.9 through 5.1.11).

TABLE 5.1

Extension Wire Tests in Water

DWM014A.WQ! Extension Wire Tests in Water @ 0.6 m/s (2fps)

Filename	Tag No. AF#	Type	Current (Amps)	Heat Time (Sec.)	Wire Length (Meters)	Plunge (Sec.)	Tc (Sec.)	Diff. (Sec.)	O.D. (mm)	Loop Res. (Ohms)
EXT1001	07	K	1.5	15	6m (20')	2.72	2.2	0.5	5	13.00
EXT1002	07	K	1.5	15	9m (30')	2.72	2.7	0.0	5	19.40
EXT1006	07	K	1.5	15	15m (50')	2.72	2.0	0.7	5	24.70
EXT1003	04	K	1.5	15	6m (20')	3.06	2.6	0.5	6	14.10
EXT1004	04	K	1.5	15	9m (30')	3.06	1.8	1.3	6	19.50
EXT1005	04	K	1.5	15	15m (50')	3.06	1.7	1.4	6	25.20
EXT1007	27	E	1.5	15	6m (20')	2.00	2.0	0.0	5	15.80
EXT1008	27	E	1.5	15	9m (30')	2.00	2.2	-0.2	5	23.30
EXT1009	27	E	1.5	15	15m (50')	2.00	2.2	-0.2	5	37.30
EXT3010	44	E	1.5	15	6m (20')	2.10	2.6	-0.5	6	15.40
EXT3011	44	E	1.5	15	9m (30')	2.10	2.5	-0.4	6	23.30
EXT3012	44	E	1.5	15	15m (50')	2.10	2.4	-0.3	6	36.90
EXT2013	38	J	1.5	15	6m (20')	1.43	0.7	0.7	5	9.90
EXT2014	36	J	1.5	15	9m (30')	1.43	0.7	0.7	5	13.50
EXT2015	36	J	1.5	15	15m (50')	1.43	0.9	0.5	5	20.70
EXT2016	38	J	1.5	15	6m (20')	1.90	1.3	0.8	3	9.30
EXT2017	38	J	1.5	15	9m (30')	1.90	1.3	0.6	3	13.20
EXT2018	38	J	1.5	15	15m (50')	1.90	1.4	0.5	3	20.10

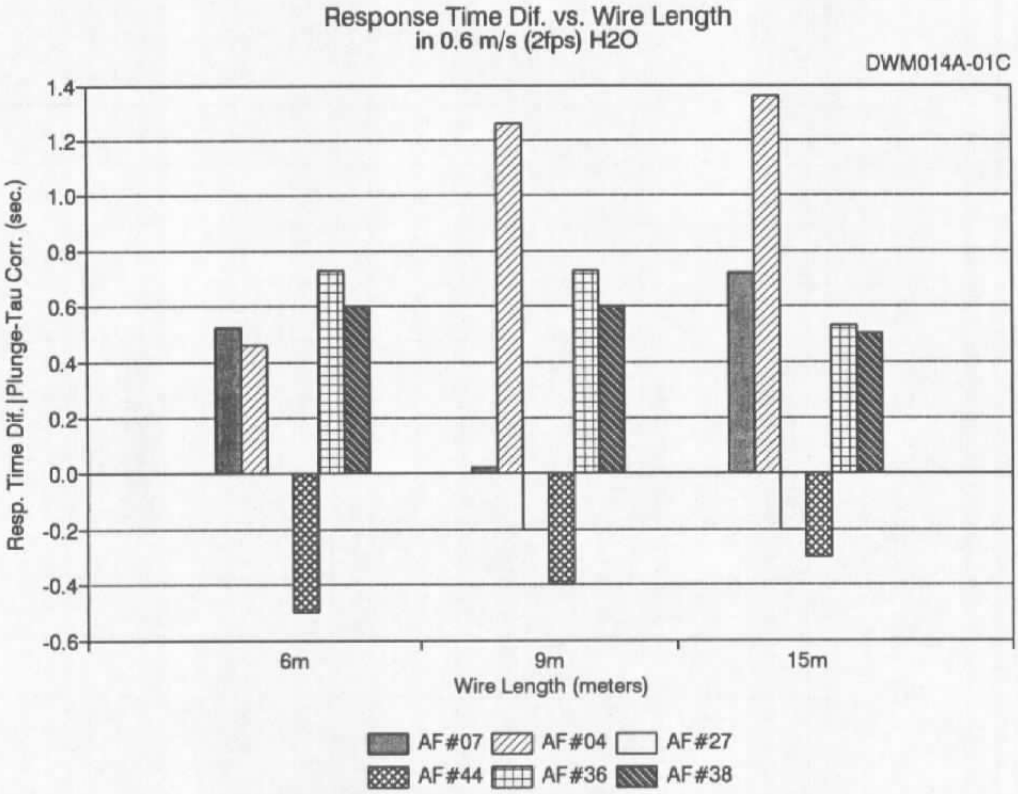


Figure 5.1.1. Response Time Difference Versus Extension Wire Length for Water.

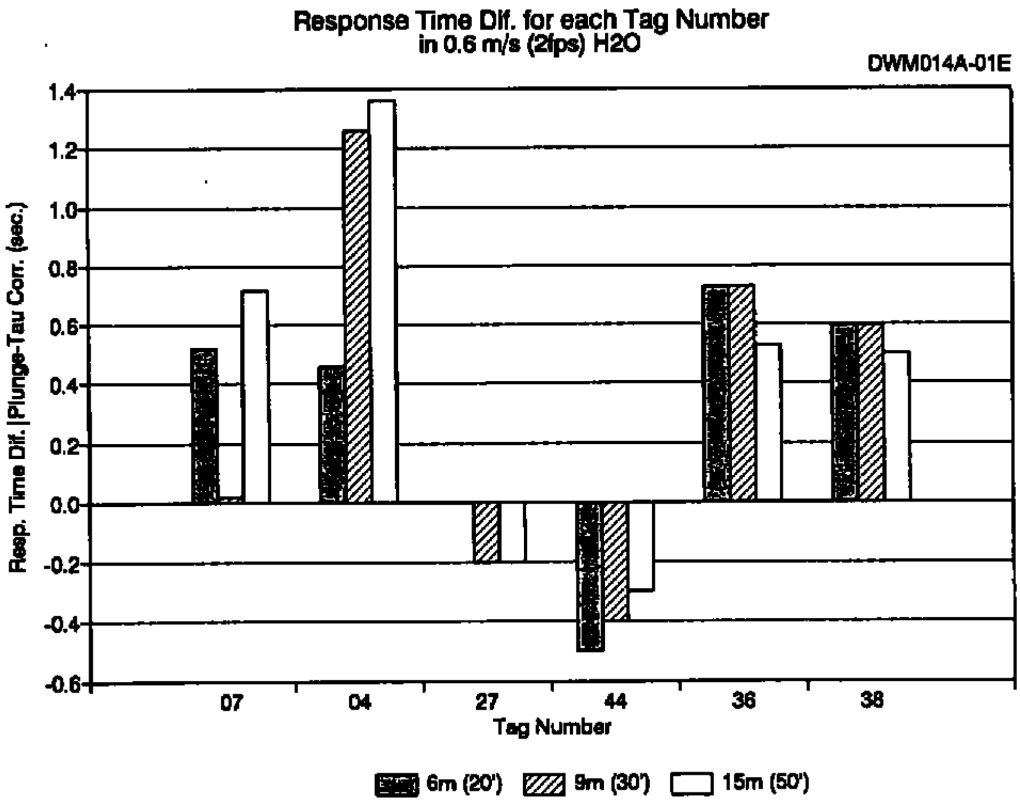


Figure 5.1.2. Response Time Difference Versus Thermocouple Tag Number for Water.

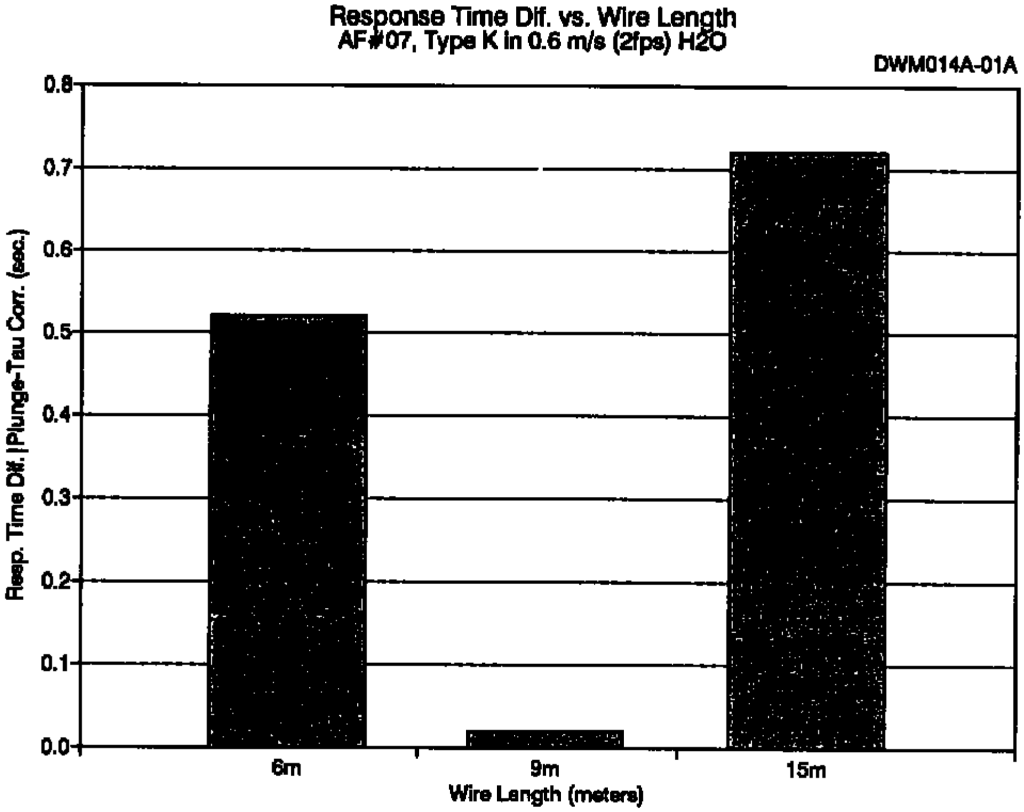


Figure 5.1.3. Response Time Difference Versus Wire Length (AF#07 in Water).

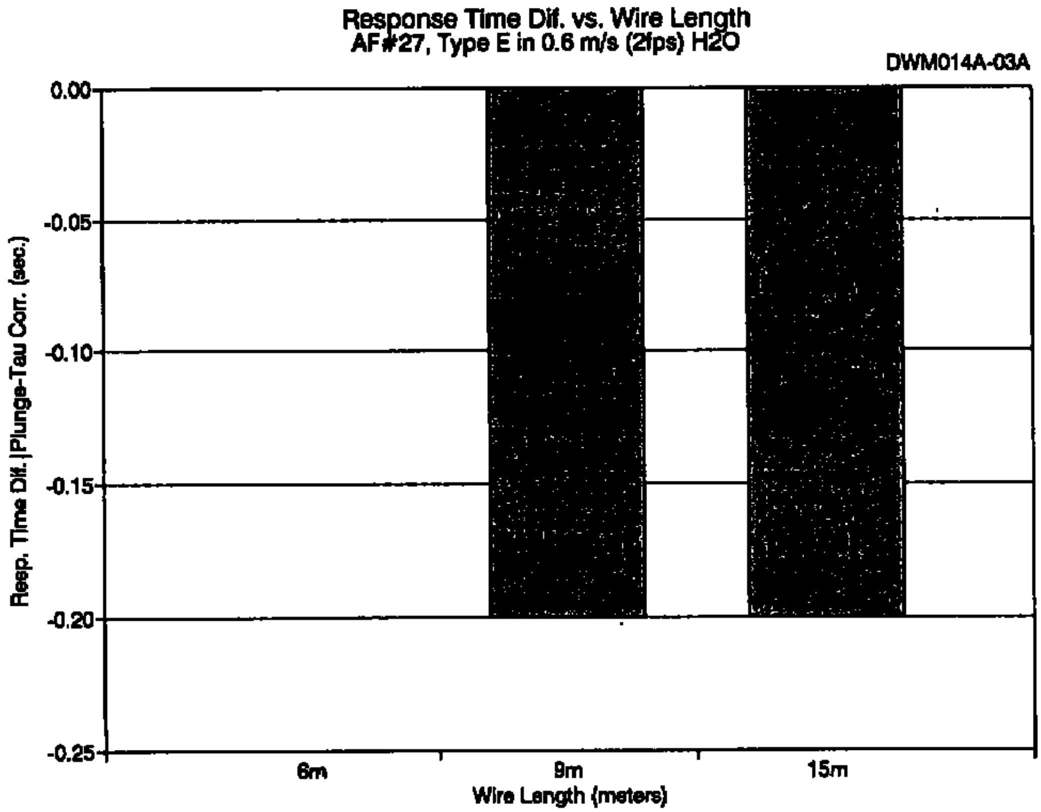


Figure 5.1.5. Response Time Difference Versus Wire Length (AF#27 In Water).

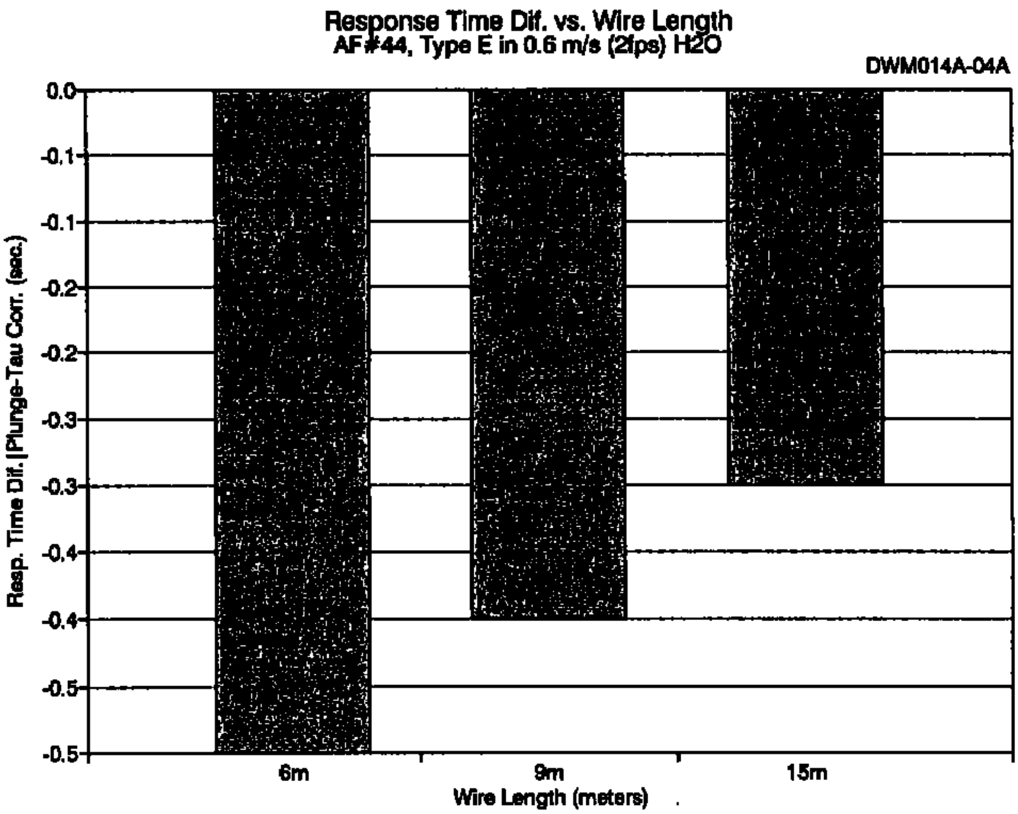


Figure 5.1.6. Response Time Difference Versus Wire Length (AF#44 in Water).

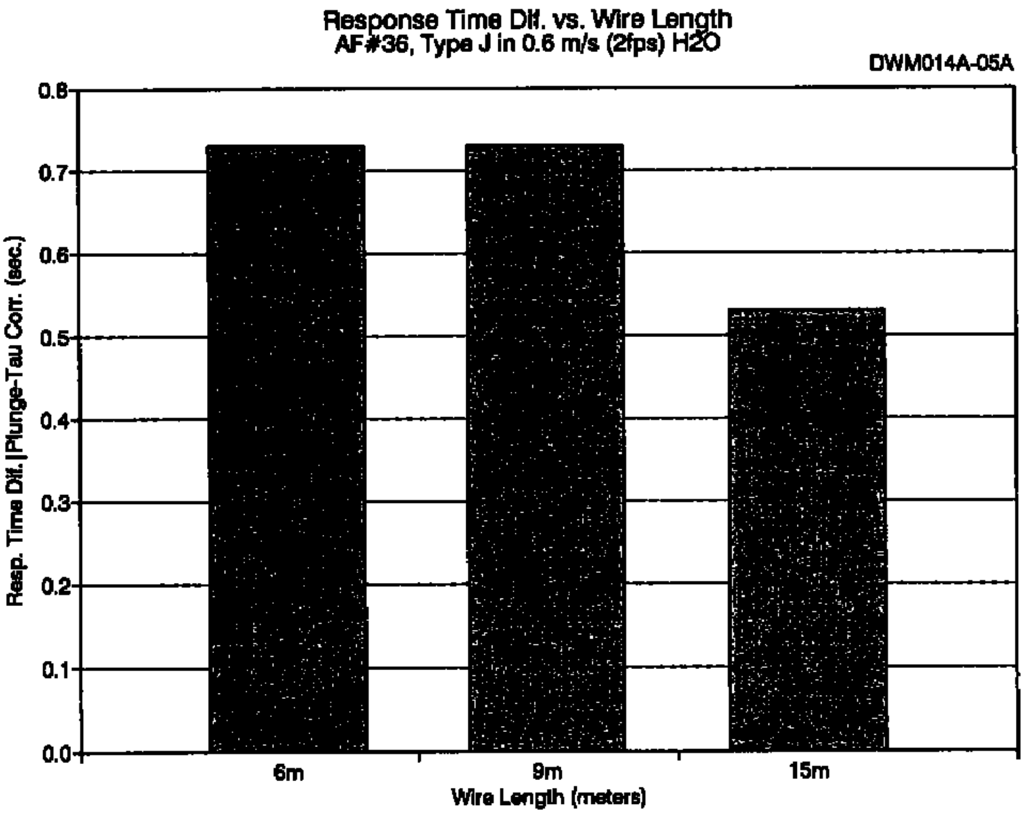


Figure 5.1.7. Response Time Difference Versus Wire Length (AF#36 in Water).

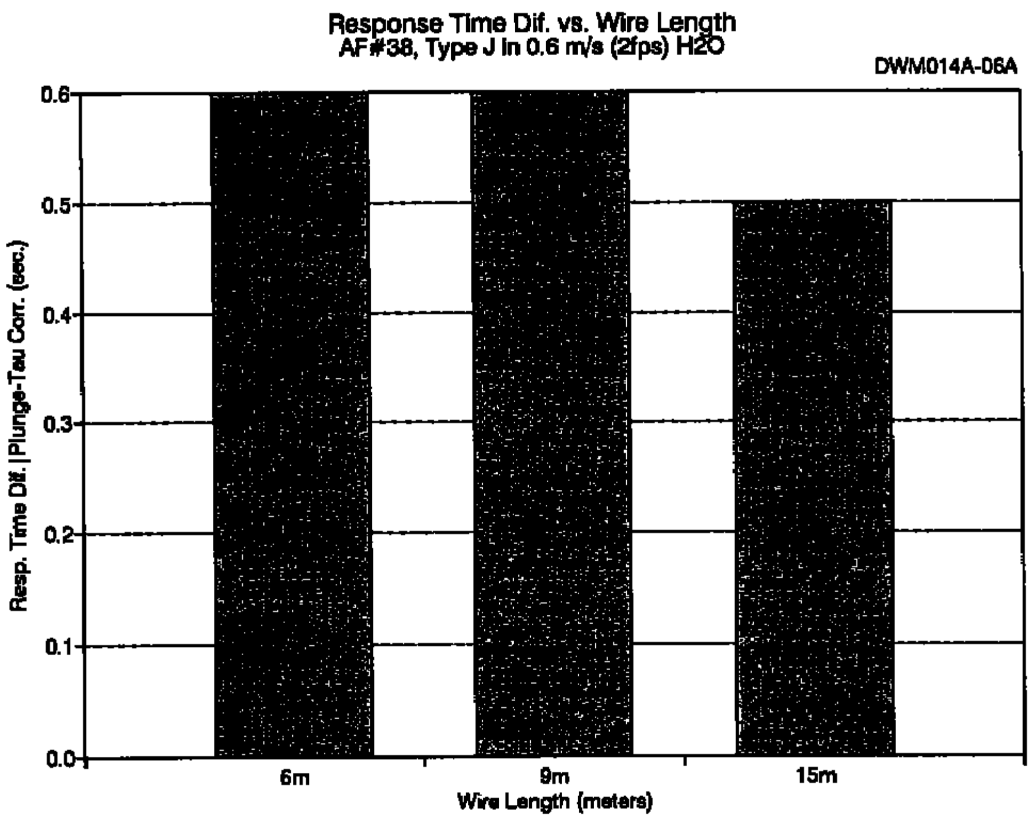


Figure 5.1.8. Response Time Difference Versus Wire Length (AF#38 in Water).

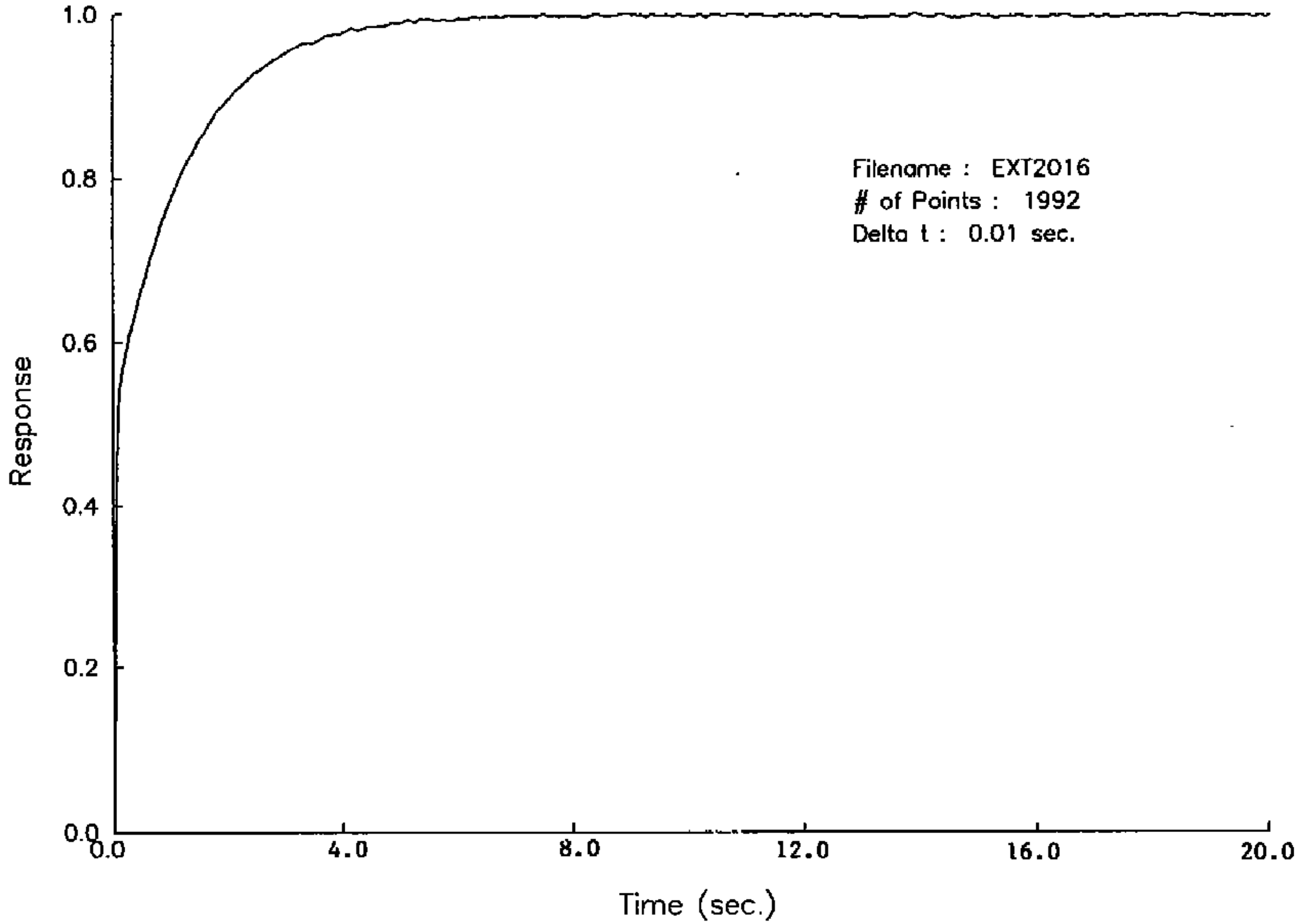


Figure 5.1.9. Averaged LCSR Transient for Sensor Tag No. AF #38 (6 meter (20') Extension Wire).

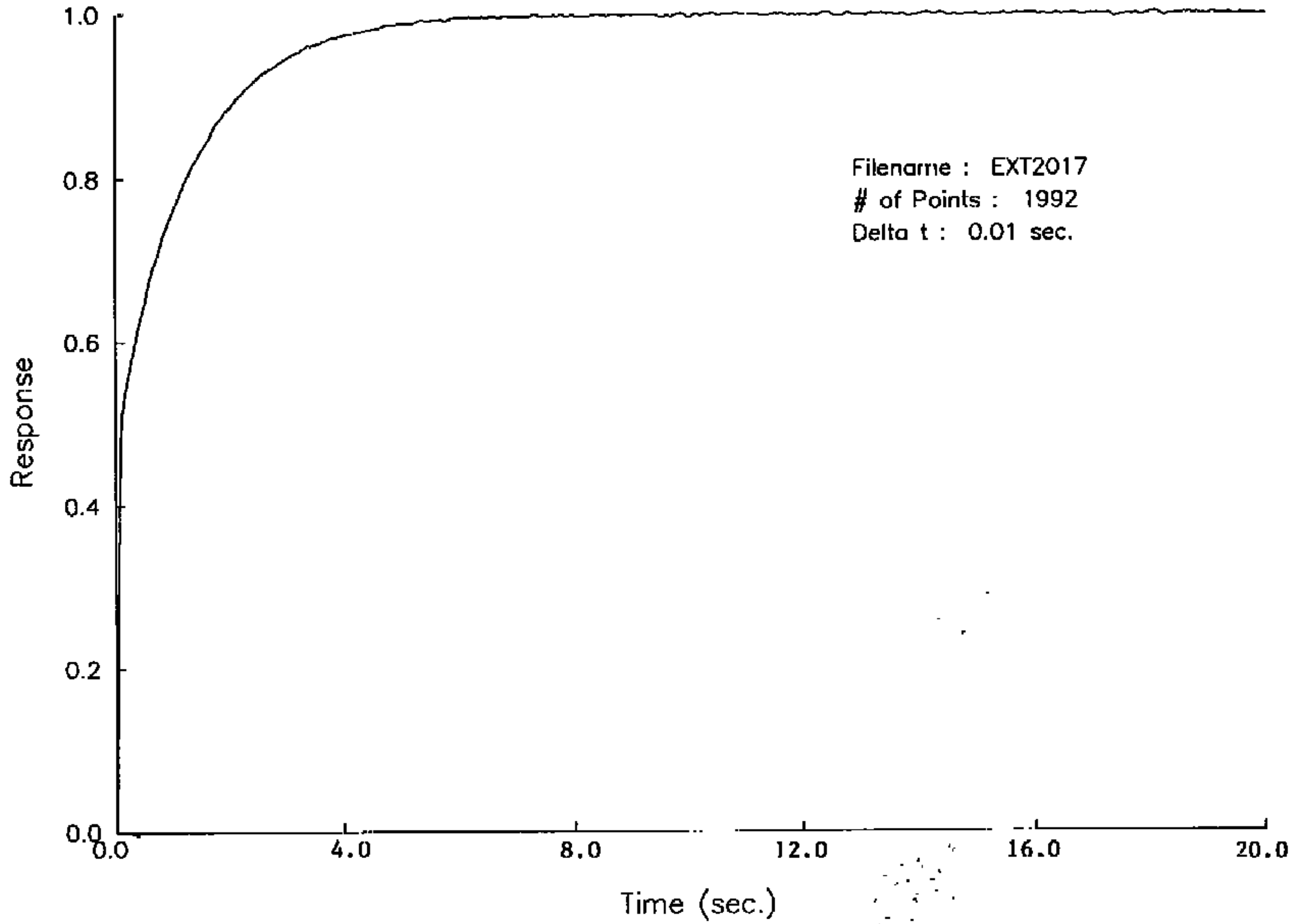


Figure 5.1.10. Averaged LCSR Transient for Sensor Tag No. AF #38 (9 meter (30') Extension Wire).

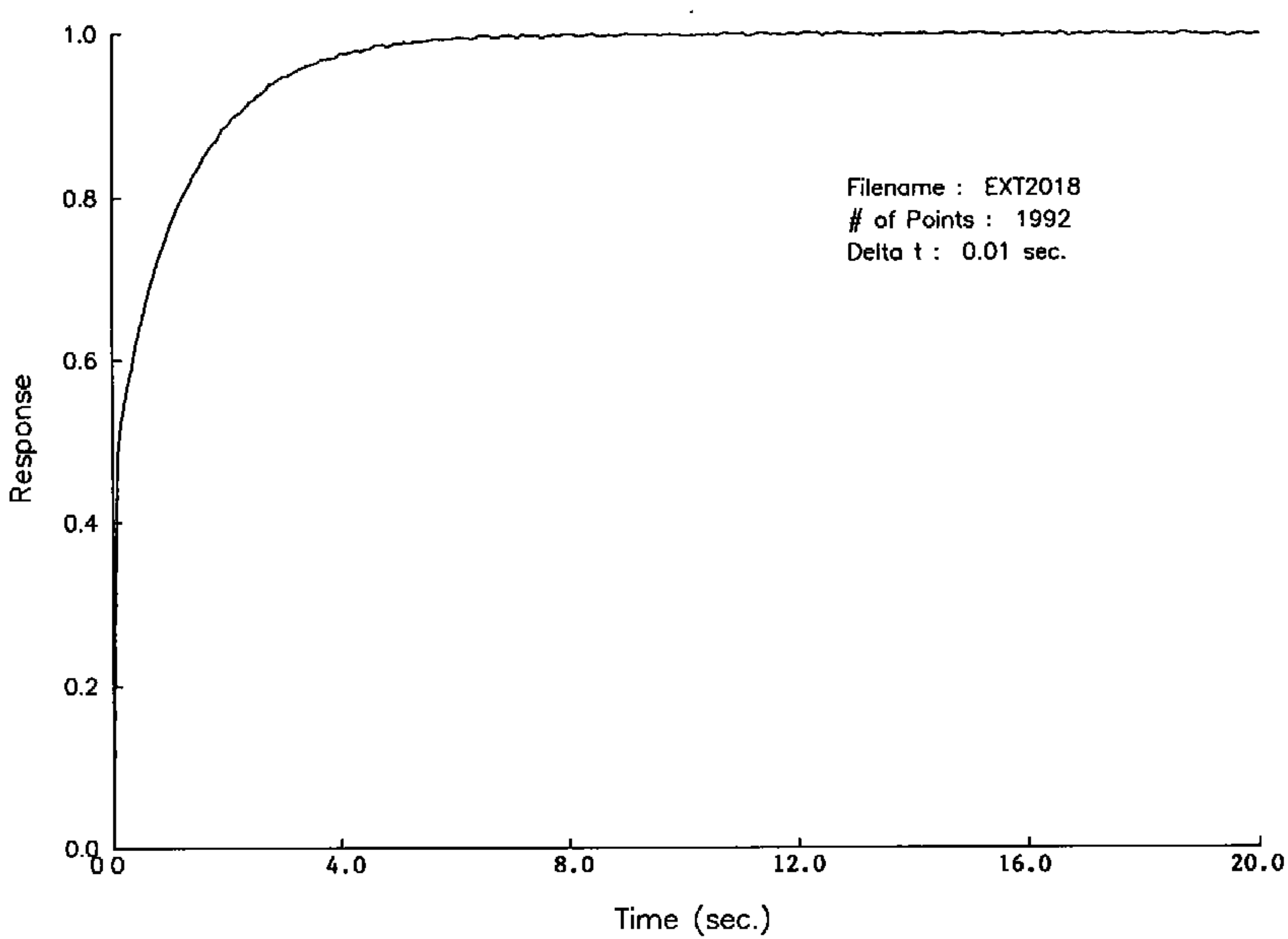


Figure 5.1.11. Averaged LCSR Transient for Sensor Tag No. AF #38 (15 meter (50') Extension Wire).

5.2 Effects in Air

The same series of extension wire tests performed in water (Section 5.1) were repeated in air. For the air tests, 14 m/sec flow was used. Table 5.2 provides the results of this testing. Graphs and plots further describing this data are shown for the following cases:

1. Composite graph of all the thermocouples tested showing response time differences versus extension wire length (Figure 5.2.1).

2. Response time differences for each thermocouple and wire length (Figure 5.2.2).

3. Response time differences for each specific thermocouple tested as wire lengths were changed (Figures 5.2.3 through 5.2.8). Note that Figures 5.2.3 and 5.2.4 also show stranded wire to assist in evaluating if extension wire type could impact LCSR results.

4. Sample LCSR traces for a typical thermocouple in air as extension wire lengths were changed (Figures 5.2.9 through 5.2.11).

Note that all of the LCSR extension wire tests performed in air provided essentially conservative results.

TABLE 5.2

Extension Wire Tests in Air

DWM014A.WQ! Extension Wire Tests in Air @ 14 m/s

Filename	Tag No. AF#	Type	Current (Amps)	Heat Time (Sec.)	Wire Length (Meters)	Voltage (Volts)	Plunge (Sec.)	Tc (Sec.)	Diff. (Sec.)	O.D. (mm)	Loop Res. (Ohms)
AXT1008	07	K	1.5	15	6m (20')	13.8	17.1	21.5	-4.4	5	9.2
AXT2001	07	K	1.5	15	6m (20')	21.5	17.1	24.5	-7.4	5	14.3
AXT2002	07	K	1.5	15	9m (30')	28.9	17.1	26.1	-9.0	5	19.3
AXT2003	07	K	1.5	15	15m (50')	45.4	17.1	26.4	-9.3	5	30.3
AXT2007	13	K	1.5	15	6m (20')	21.0	3.7	4.0	-0.3	2	14
AXT2004	13	K	1.5	15	6m (20')	26.1	3.7	4.1	-0.4	2	17.4
AXT2005	13	K	1.5	15	9m (30')	35.1	3.7	4.1	-0.4	2	23.4
AXT2006	13	K	1.5	15	15m (50')	52.1	3.7	3.9	-0.2	2	34.7
AXT2009	27	E	1.6	15	6m (20')	24.3	17.1	22.6	-5.5	5	16.2
AXT2010	27	E	1.5	15	9m (30')	34.1	17.1	21.8	-4.7	5	22.7
AXT2011	27	E	1.5	15	15m (50')	55.4	17.1	24.3	-7.2	6	36.9
AXT2012	43	E	1.5	15	6m (20')	32.3	3.9	4.2	-0.3	2	21.5
AXT2013	43	E	1.5	15	9m (30')	43.2	3.9	3.9	0.0	2	28.8
AXT2014	43	E	1.5	15	15m (50')	64.5	3.9	3.9	0.0	2	43
AXT1015	36	J	1.5	15	6m (20')	15.0	17.5	26.2	-8.7	5	10
AXT1016	36	J	1.5	15	9m (30')	20.0	17.5	22.9	-5.4	5	13.3
AXT1017	36	J	1.5	15	15m (50')	30.8	17.5	21.3	-3.8	5	20.5
AXT2018	40	J	1.5	15	6m (20')	16.7	3.2	4.0	-0.8	2	11.1
AXT2019	40	J	1.5	15	9m (30')	22.3	3.2	4.0	-0.8	2	14.9
AXT2020	40	J	1.5	15	15m (50')	33.6	3.2	4.0	-0.8	2	22.4

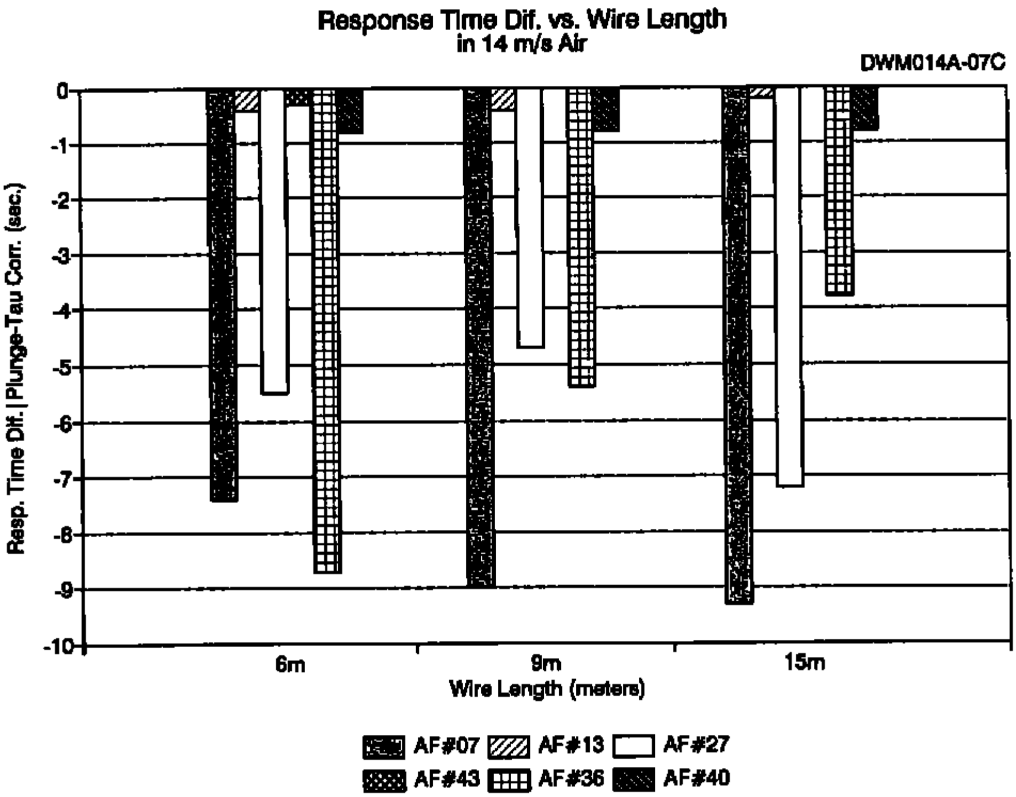


Figure 5.2.1. Response Time Difference Versus Wire Length for Air.

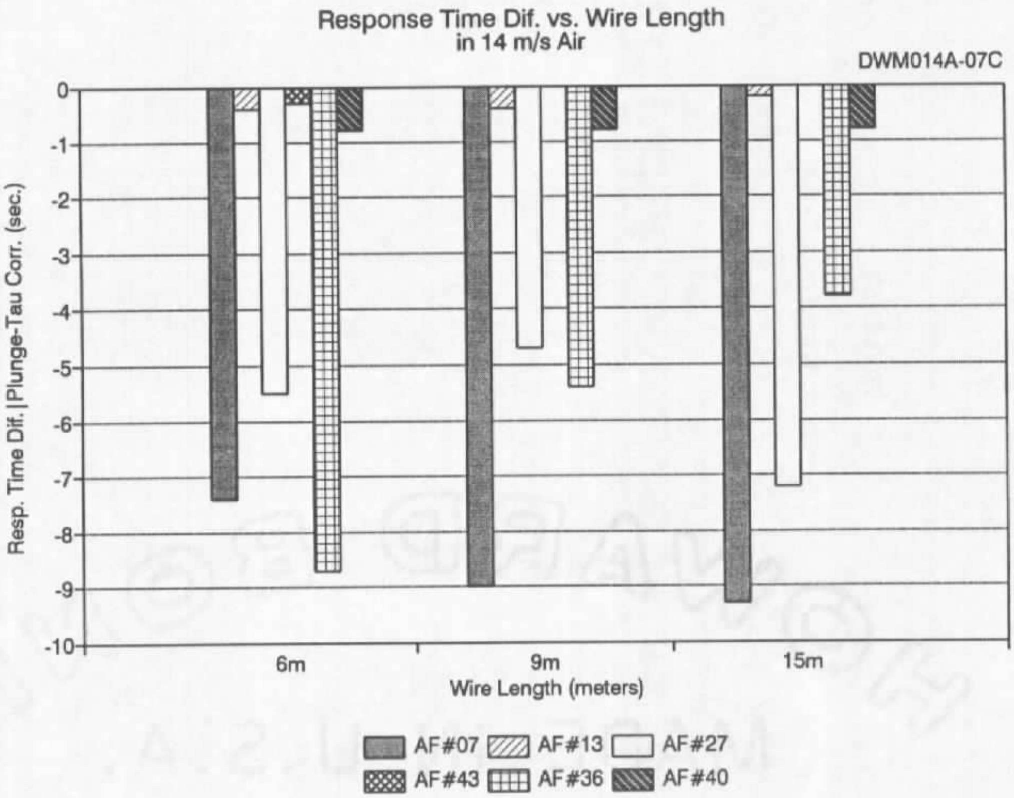


Figure 5.2.1. Response Time Difference Versus Wire Length for Air.

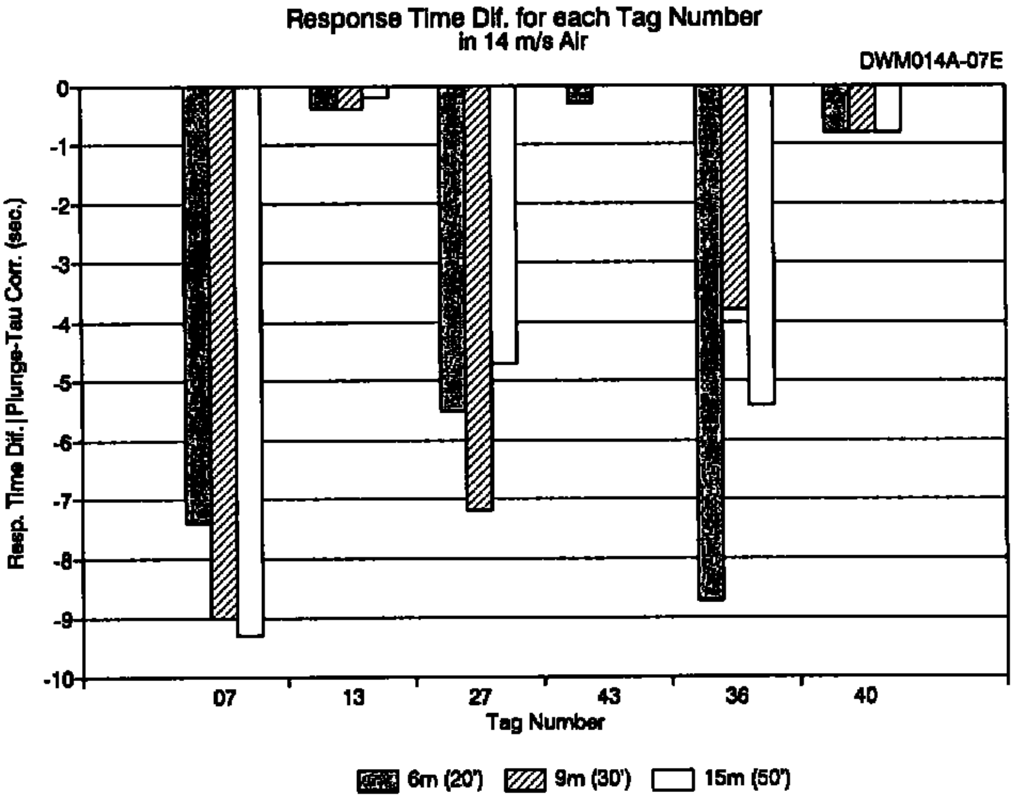


Figure 5.2.2. Response Time Difference Versus Tag Number for Air.

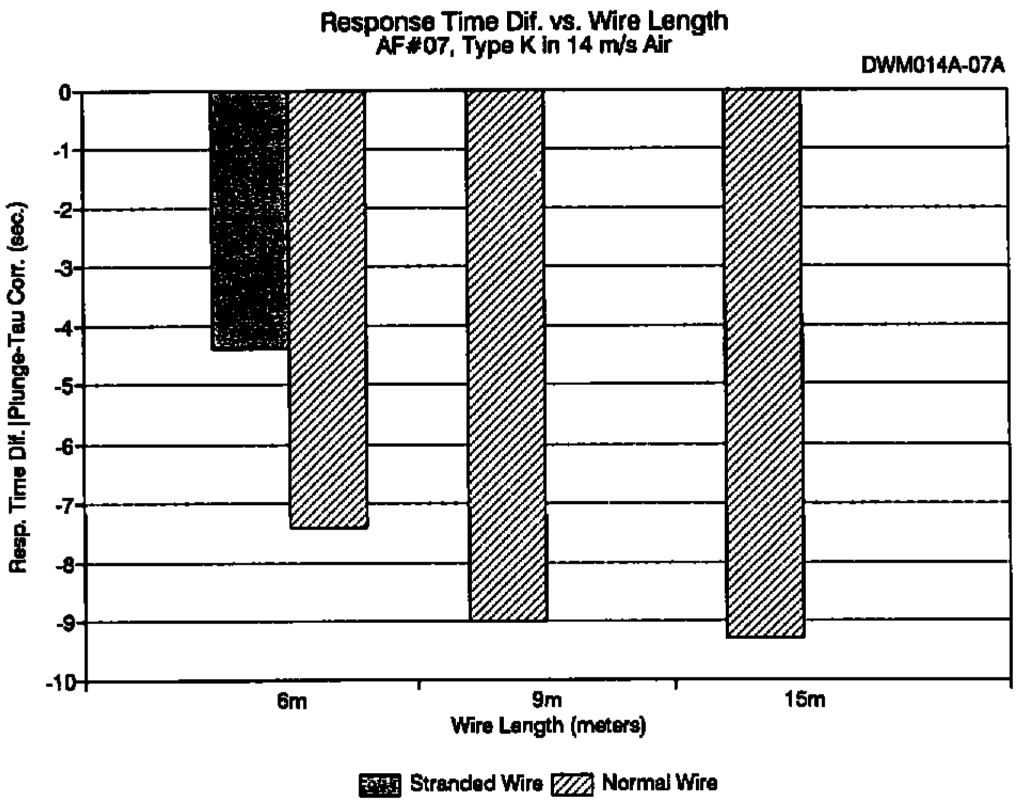


Figure 5.2.3. Response Time Difference Versus Wire Length (AF#07 in Air).

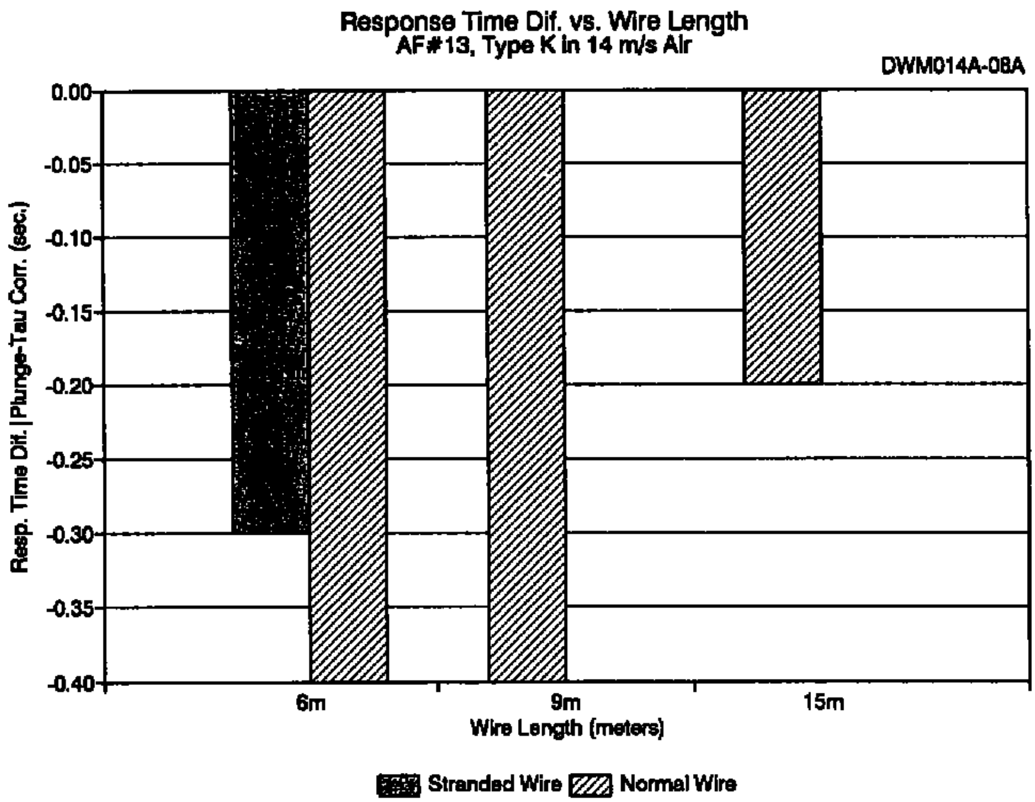


Figure 5.2.4. Response Time Difference Versus Wire Length (AF#13 in Air).

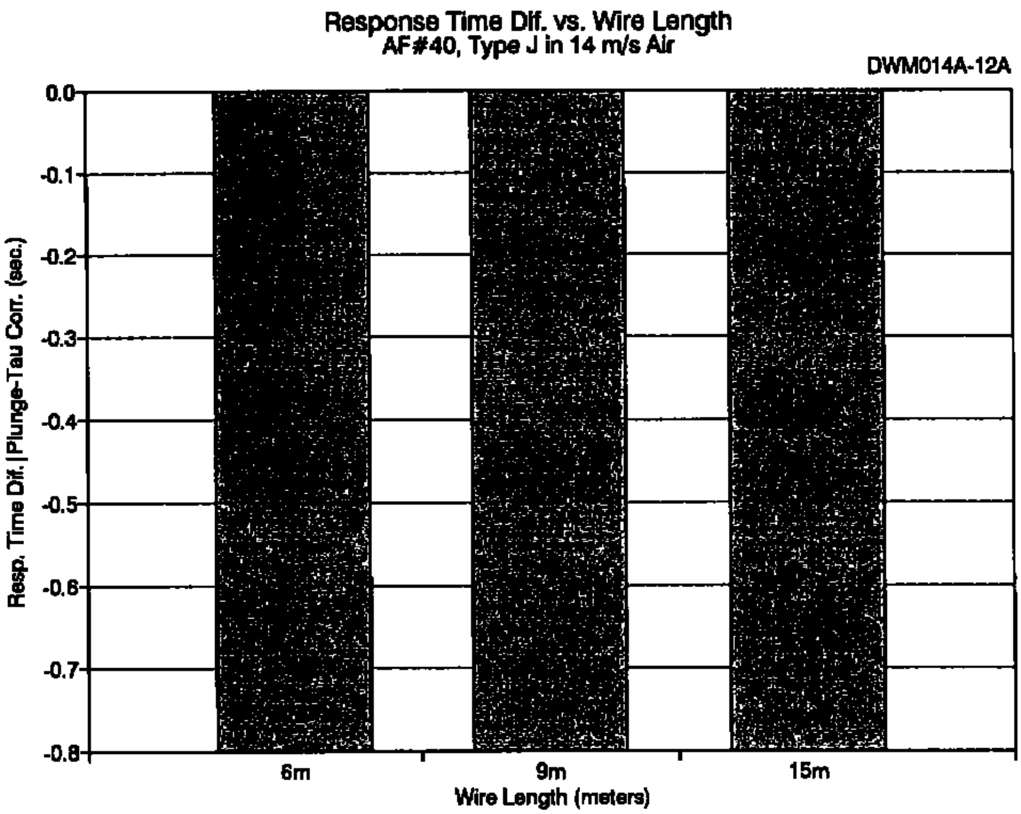


Figure 5.2.5. Response Time Difference Versus Wire Length (AF#40 in Air).

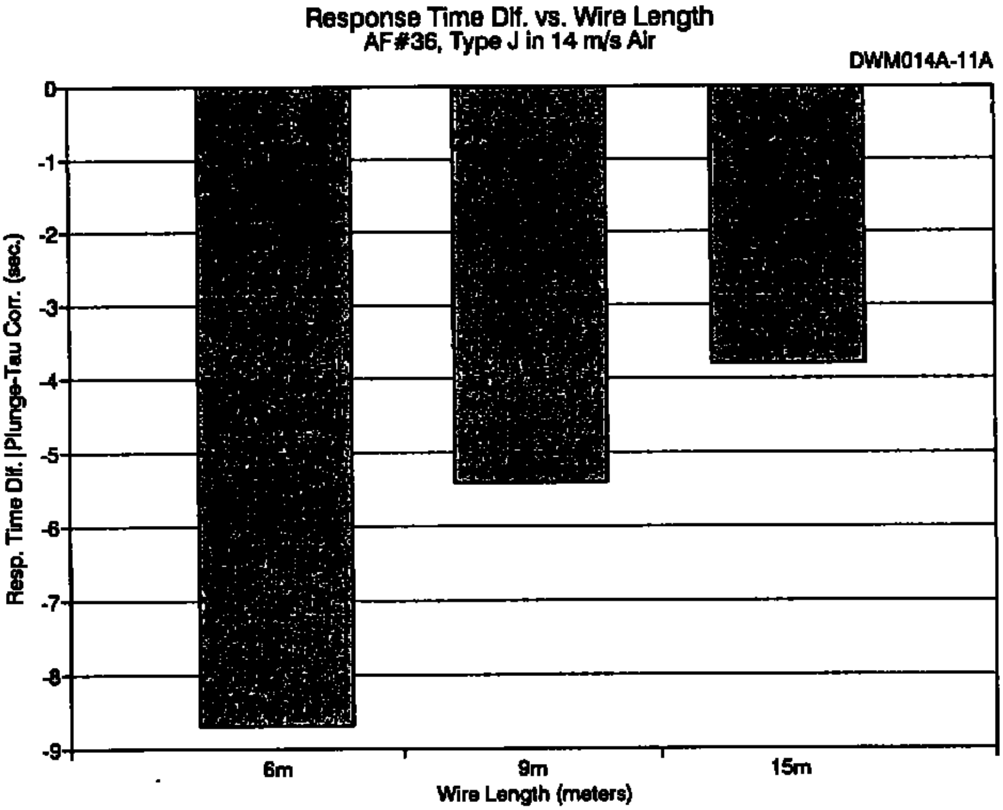


Figure 5.2.6. Response Time Difference Versus Wire Length (AF#36 in Air).

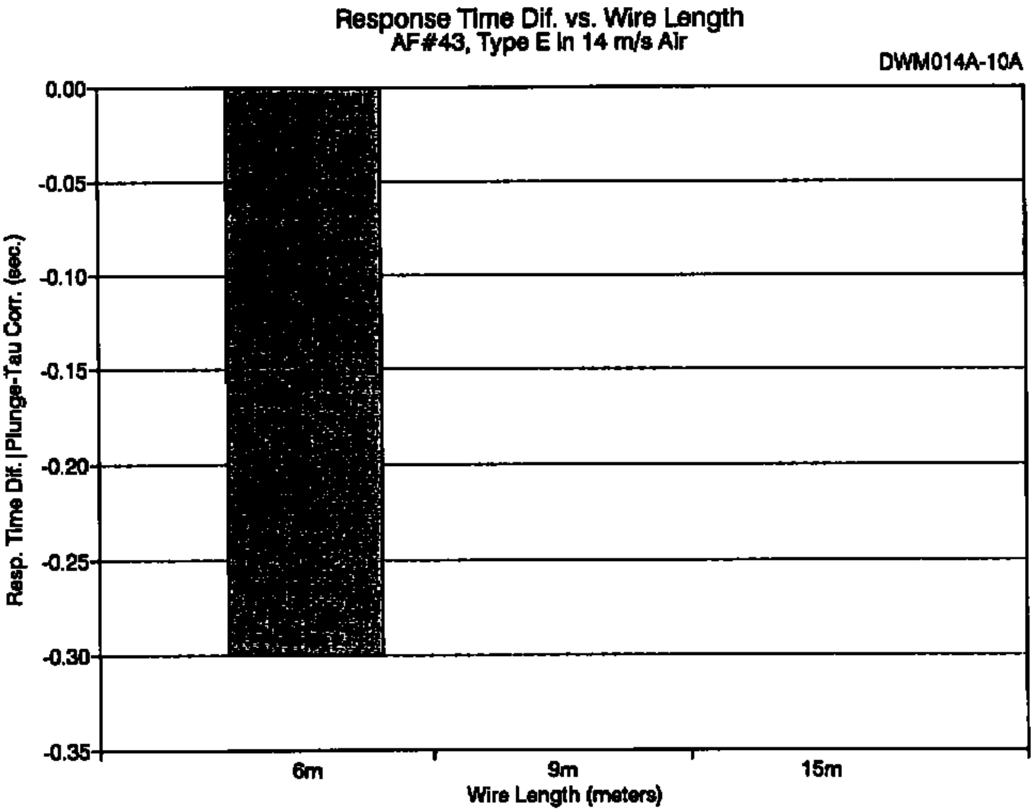


Figure 5.2.7. Response Time Difference Versus Wire Length (AF#43 in Air).

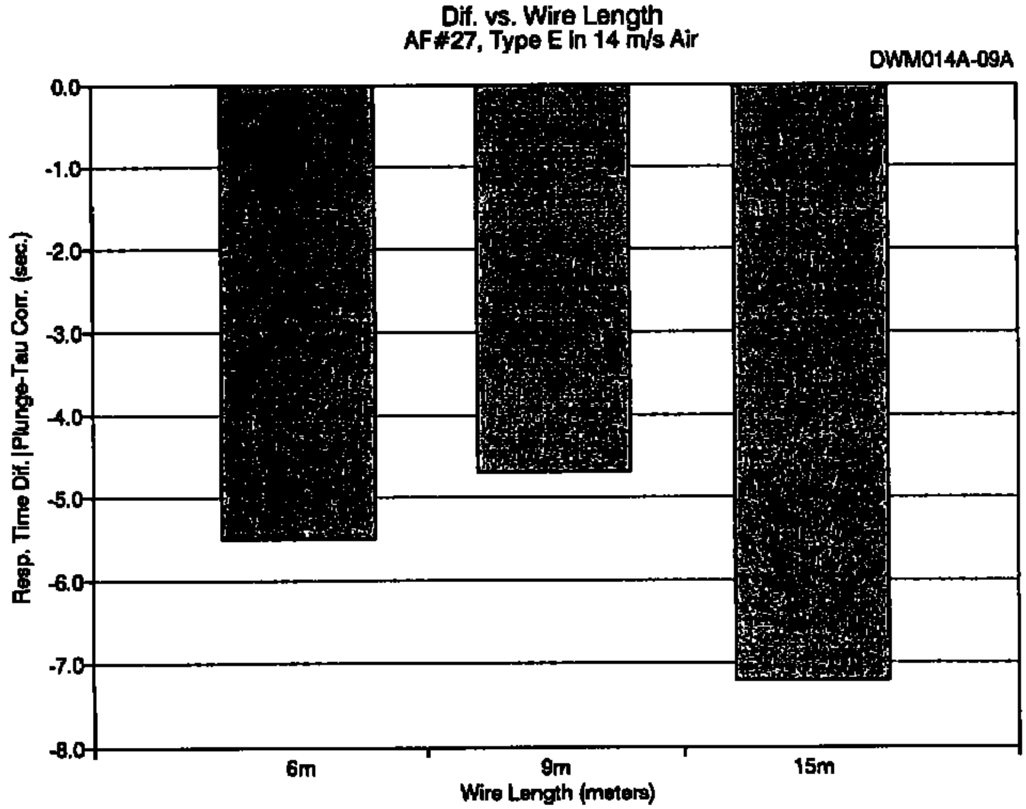


Figure 5.2.8. Response Time Difference Versus Wire Length (AF#27 in Air).

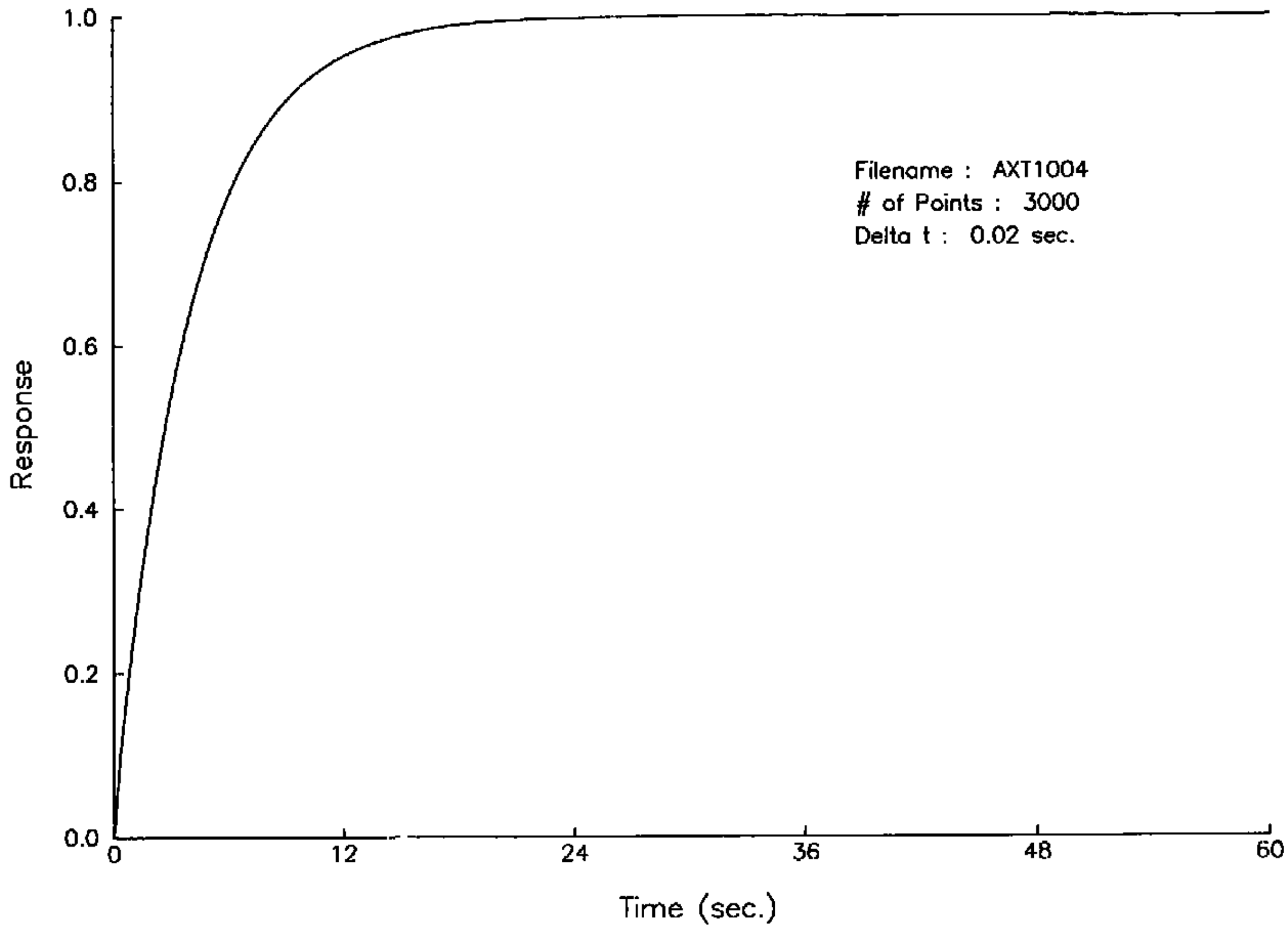


Figure 5.2.9. Averaged LCSR Transient for Sensor Tag No. AF #13 (6 meter (20') Extension Wire).

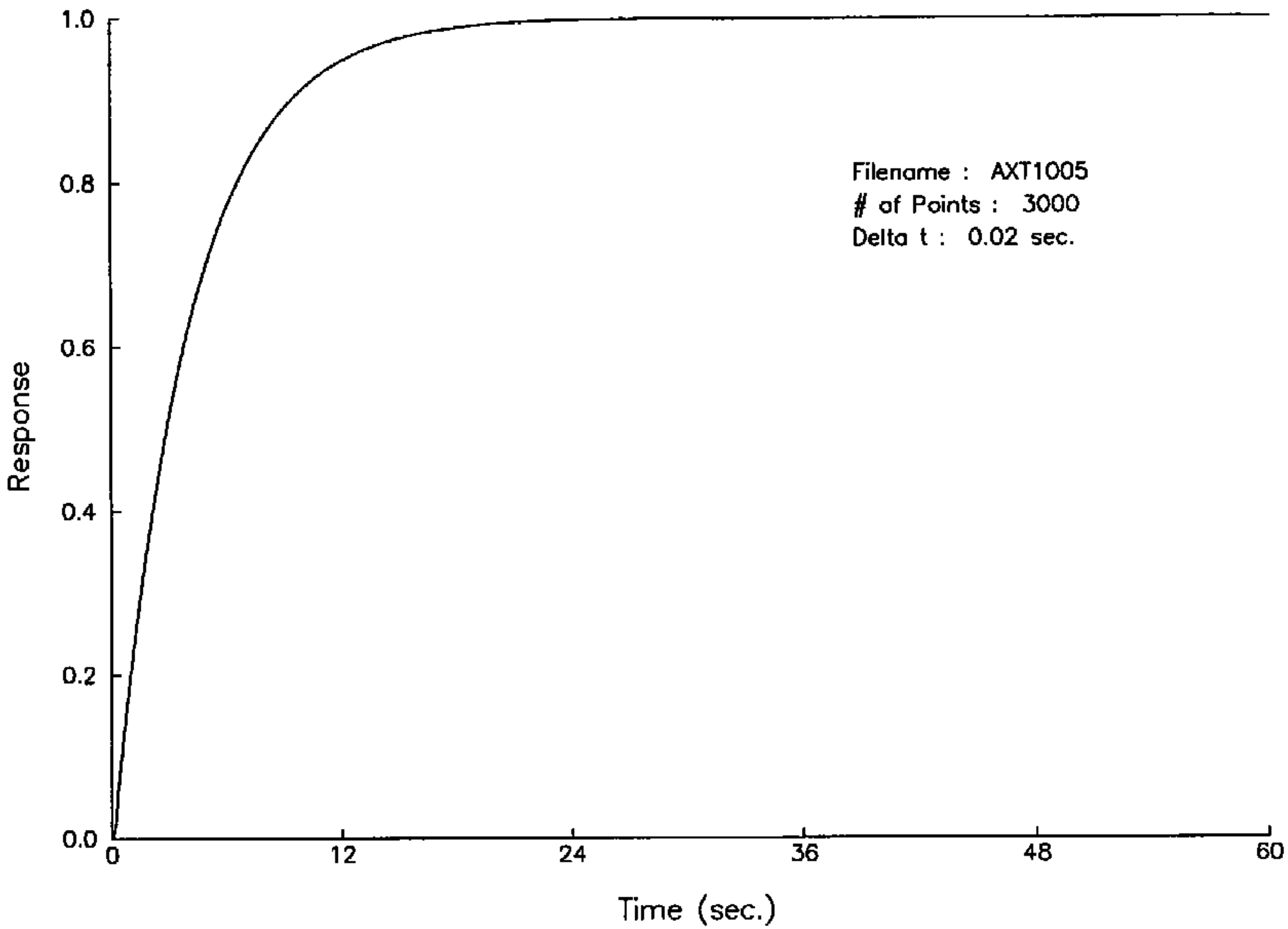


Figure 5.2.10. Averaged LCSR Transient for Sensor Tag No. AF #13 (9 meter (30') Extension Wire).

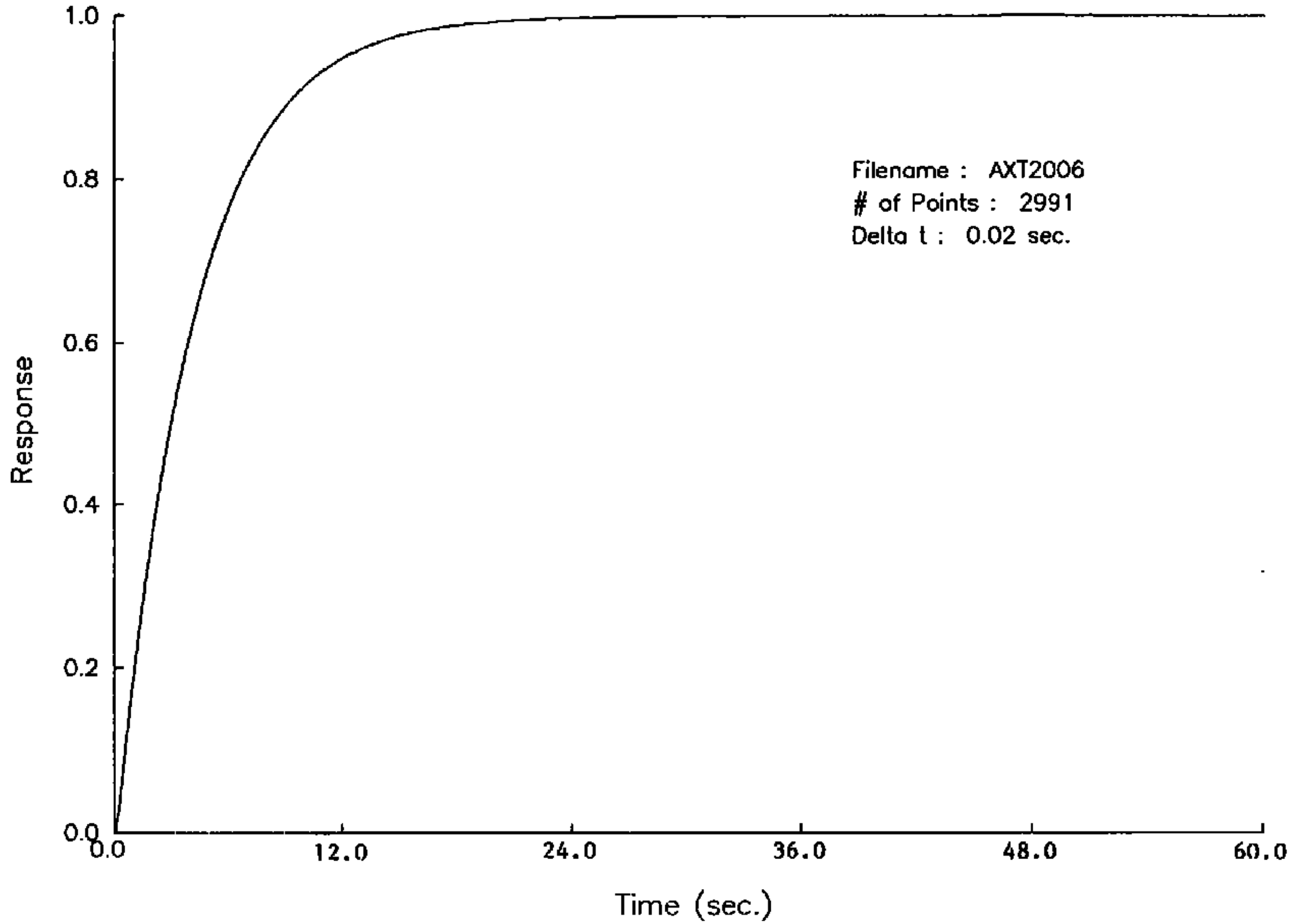


Figure 5.2.11. Averaged LCSR Transient for Sensor Tag No. AF #13 (15 meter (50') Extension Wire).

6. THERMOCOUPLE LCSR IN HIGH AIR FLOW RATES

Many applications require the use of thermocouples in high subsonic or supersonic air flows. A series of tests were performed to prove the viability of the LCSR technique for response time testing of thermocouples in these environments.

6.1 Supersonic Air Flow

For the supersonic tests, a total of six thermocouples were selected. Testing was performed using AMS and University of Tennessee Mechanical and Aerospace Engineering Department facilities. The sequence of events for these tests was as follows:

1. Subsonic testing of the selected thermocouples using 18 m/sec flow in the AMS wind tunnel was performed. Both plunge test and LCSR data were acquired (Table 6.1).

2. Response time testing of the thermocouples (using the LCSR method) was performed in the supersonic wind tunnel at the University of Tennessee using Mach 2 air flow. This wind tunnel could not be used to perform plunge tests, therefore the LCSR method is the only method which could be used to provide an indication of the response time of the thermocouples in these conditions. Typical (non-averaged) LCSR transients are shown in Figures 6.1.1 and 6.1.2. The results are shown in Table 6.2.

3. The plunge test data from step 1 above were fitted to the following equation to obtain the constants C_1 and C_2 for each thermocouple:

$$\tau = C_1 + C_2/h$$

Where h represents the film heat transfer coefficient and τ is the time constant.

The procedure used to fit the plunge test data to this equation is essentially the same as that described in Section 2.1, except the heat transfer coefficient is now the independent variable in lieu of the flow rate. This technique provided calculated estimates for the time constant at higher velocities (and different heat transfer coefficients). These calculated values were subsequently compared to actual LCSR results for four of the thermocouples and are shown in Table 6.3. Note that the calculations for AF #21 were not performed.

TABLE 6.1

AMS Subsonic Tests
(18 m/s Air Flow)

Tag #	Type	Loop Resistance	Wire O.D.	Sheath O.D.	Plunge Results	LCSR Results
AF #18	K	122.0Ω	0.10mm	0.51mm	0.15	0.19
AF #19	K		0.10mm	0.51mm		
AF #20	K	121.0Ω	0.10mm	0.51mm	0.15	0.12
AF #21	K	294.0Ω	0.10mm	0.51mm	0.60	0.58
AF #22	K	20.4Ω	0.32mm	1.60mm	0.44	0.38
AF #23	K	20.0Ω	0.32mm	1.60mm	0.44	0.41

Notes:
1. AF #19 failed open during testing.
2. Plunge and LCSR results are in seconds.
3. Plunge and LCSR results are for 18 m/sec air flow.

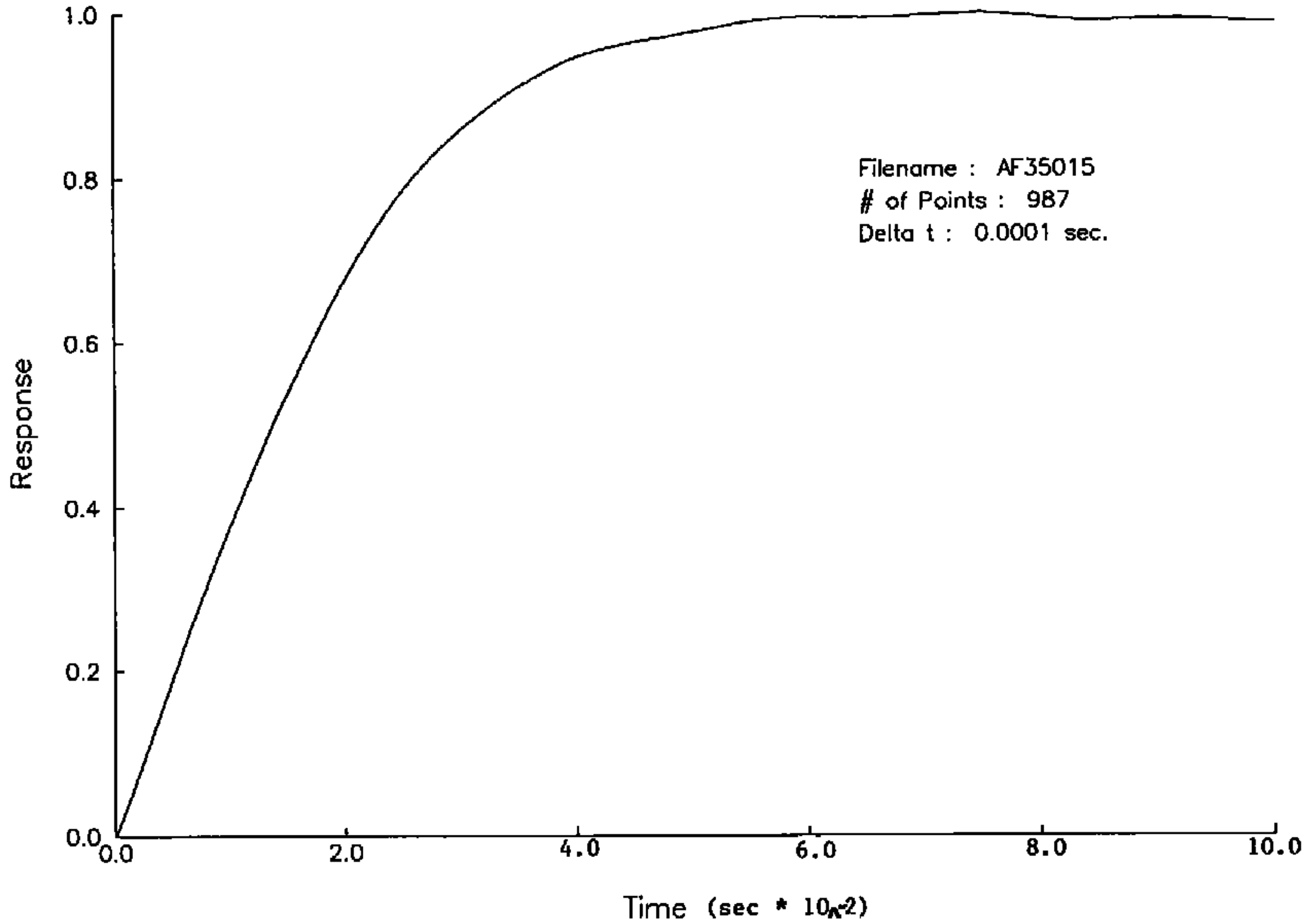


Figure 6.1.1. Raw LCSR Transient for Sensor Tag No. AF #20 (Mach 2) .

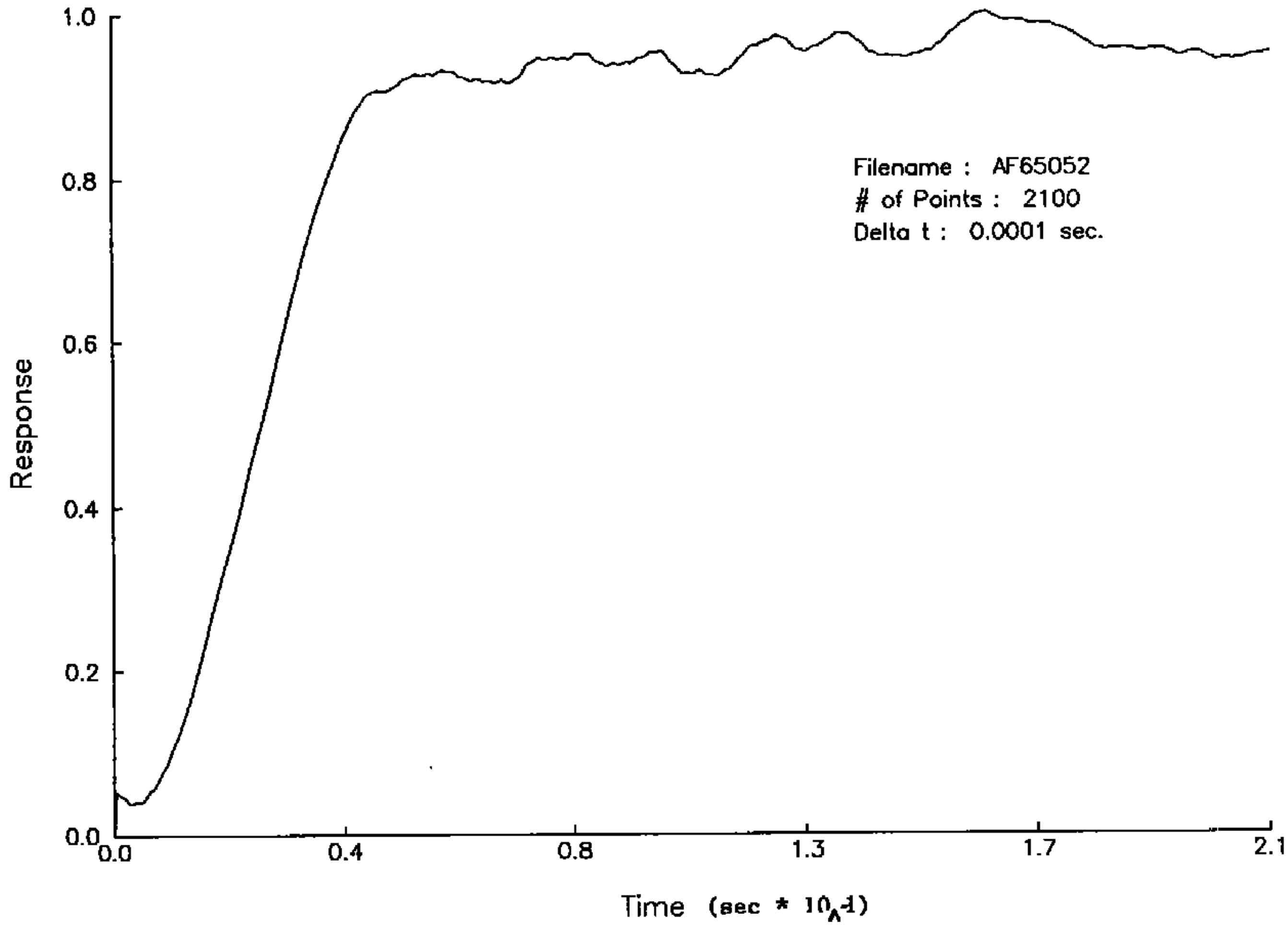


Figure 6.1.2. Raw LCSR Transient for Sensor Tag No. AF #23 (Mach 2) .

TABLE 6.2

Results from Supersonic Wind Tunnel at Mach 2

Tag #	LCSR Time Constant (sec)
AF #18	0.05
AF #20	0.04
AF #21	0.07
AF #22	0.06
AF #23	0.08

TABLE 6.3

**Actual Versus Calculated Time Constants
(Mach 2)**

Tag #	Time Constant (sec) LCSR	Time Constant (sec) Calculated
AF #18	0.05	0.05
AF #20	0.04	0.05
AF #22	0.06	0.06
AF #23	0.08	0.06

6.2 Subsonic Air Flow

In addition to the subsonic air flow testing described in Section 3.4, several additional tests were performed to verify the capabilities of the LCSR method in high subsonic air flows. To perform this work, a subsonic wind tunnel at the University of Tennessee was utilized. In all, a total of 7 thermocouples and 3 different air speeds (27 m/s, 45 m/s and 54 m/s) were used. The results are shown in Table 6.4. Graphs showing the comparisons between LCSR and baseline plunge results are provided in Figures 6.2.1 and 6.2.2.

TABLE 6.4

Subsonic Air Flow Test Results

Tag #	Type	Gage	27m/sec Plunge	27m/sec LCSR	45m/sec Plunge	45m/sec LCSR	54m/sec Plunge	54m/sec LCSR
AF #14	K	24	1.40	1.20	1.20	2.00		
AF #15	K	30	0.70	0.80	0.40	0.30		
AF #16	K	20	1.70	1.50	1.10	1.00		
AF #18	K		0.08	*	0.08	*		
AF #22	K		0.40	0.46	0.27	0.37		
AF #29	E	23	8.00	9.13			6.00	6.30
AF #40	J	30	2.45	4.40	2.22	3.00		

* Due to the extremely fast time constant at this flow rate, accurate correlation of LCSR data to plunge test results was not possible using existing plunge test equipment.

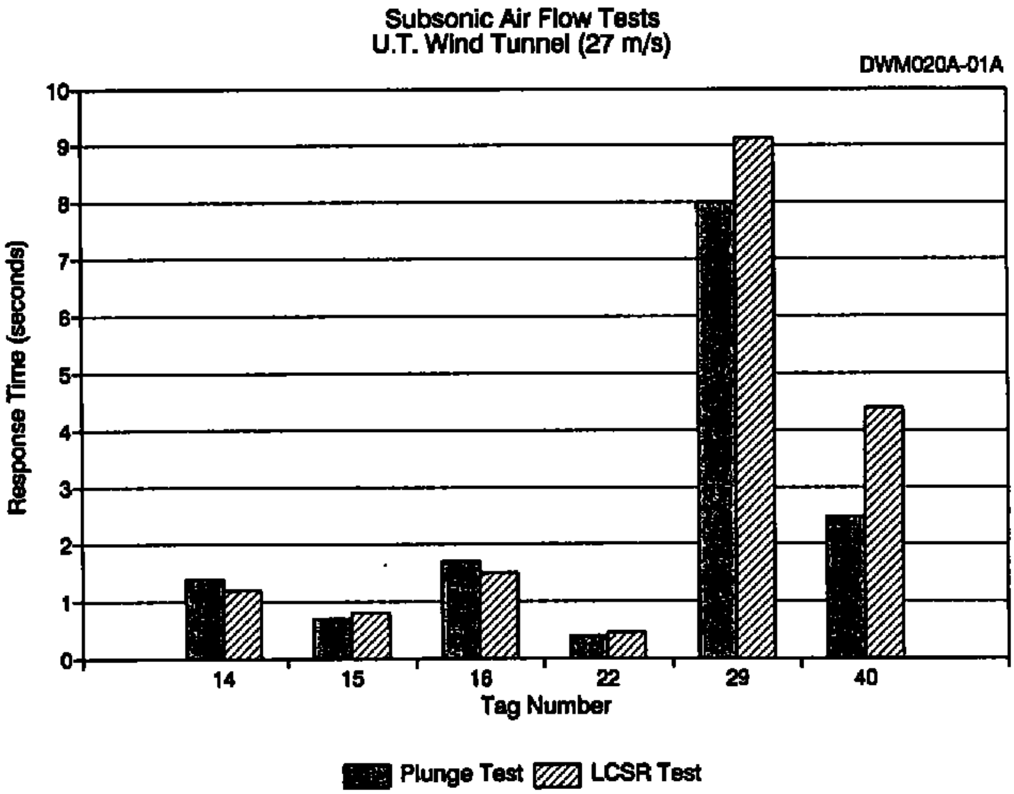


Figure 6.2.1. Subsonic Air Flow Tests (27 m/s).

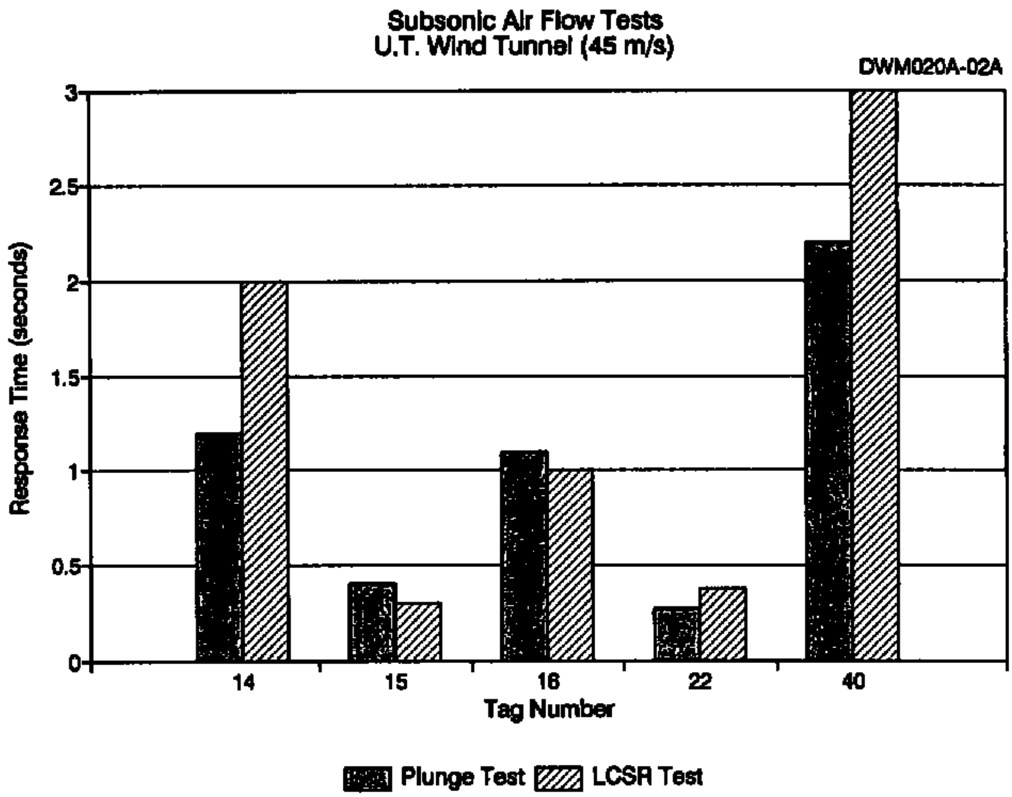


Figure 6.2.2. Subsonic Air Flow Tests (45 m/s).

7. REPEATABILITY OF LCSR MEASUREMENTS FOR THERMOCOUPLES

The repeatability of a test is determined by the consistency of the results when test conditions are held constant; several tests were performed to determine the repeatability of LCSR measurements for thermocouples.

The tests were performed at two different times: initial sequential tests (three LCSR tests performed one right after the other), and after one week. All of the tests were performed using the newly developed microprocessor test system since the data acquisition parameters could be easily held constant for each test. The parameters were chosen based on a developed procedure described in Volume 3. The results are provided as follows:

1. Sequential repeatability tests in water and air (Tables 7.1 and 7.2). The LCSR tests shown here were performed three times in both water (0.6 m/s) and air (14 m/s). These tables are shown in graphical form in Figures 7.1 and 7.2. Note that the averages of the three sequential LCSR tests are also shown.

2. One week repeatability in water and air (Tables 7.3 and 7.4). This data represents the repeat of the LCSR tests one week after the sequential tests. These tables are graphically shown in Figures 7.3 and 7.4.

In addition to the repeatability tests noted above, tests were performed to evaluate the man-to-man repeatability of the LCSR test. Personnel other than the primary test engineers performed LCSR tests on several thermocouples (in 0.6 m/s water) using the same methods as the other repeatability tests. These results are shown in Table 7.5 and Figure 7.5. This data represents typical differences in results which could be expected by using numerous test personnel.

TABLE 7.1

Sequential LCSR Repeatability
(0.6m/s Water)

Tag#	Plunge (sec)	Test # Test 1 (sec)	Test 2 (sec)	Test 3 (sec)	LCSR Average (sec)
29	1.40	1.11	1.09	1.09	1.10
27	2.00	1.96	1.99	2.01	1.99
43	0.37	0.35	0.39	0.36	0.37
44	2.10	2.07	2.16	2.70	2.19
46	1.98	2.20	2.78	2.20	2.39
36	1.43	1.47	1.29	1.23	1.33
38	1.90	1.97	2.03	1.95	1.98
40	0.43	0.44	0.44	0.42	0.43
4	3.06	2.82	2.77	2.91	2.83
7	2.72	3.03	2.86	2.99	2.96
9	0.76	0.50	0.49	0.49	0.49
13	0.27	0.29	0.30	0.27	0.29

TABLE 7.2

Sequential LCSR Repeatability
(14m/s Air)

Tag#	Plunge (sec)	Test # One (sec)	Test # Two (sec)	Test # Three (sec)	LCSR Average (sec)
40	3.20	3.63	3.54	3.73	3.63
38	9.90	9.63	9.38	9.44	9.48
52	1.28	1.82	1.53	1.28	1.54
13	3.66	4.06	6.82	10.21	7.03
9	10.03	14.58	14.06	15.39	14.68
7	17.13	18.75	16.49	19.57	18.27
51	1.12	1.01	1.07	1.23	1.10
43	3.88	4.02	3.96	3.72	3.90
29	10.55	8.48	9.08	8.28	8.61
27	17.10	18.16	18.12	22.08	19.45
20	0.16	0.12	0.10	0.09	0.10
18	0.14	0.12	0.12	0.12	0.12
23	0.50	0.56	0.46	0.47	0.50

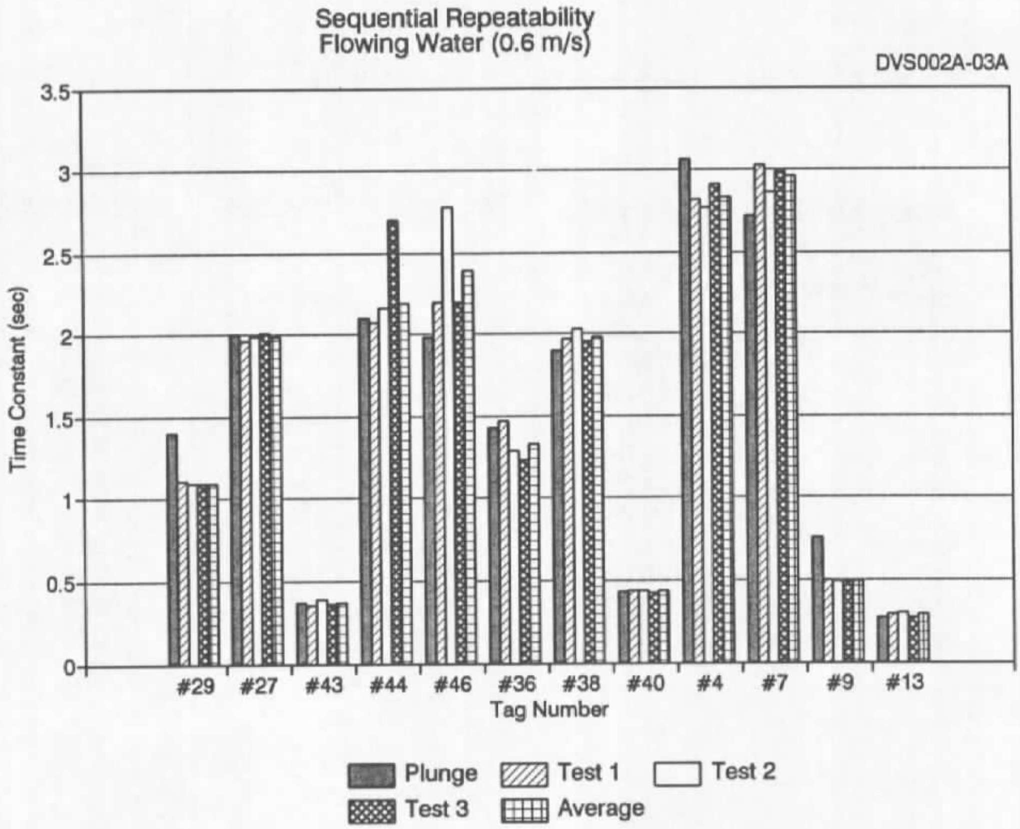


Figure 7.1. Sequential Repeatability (0.6 m/s Water).

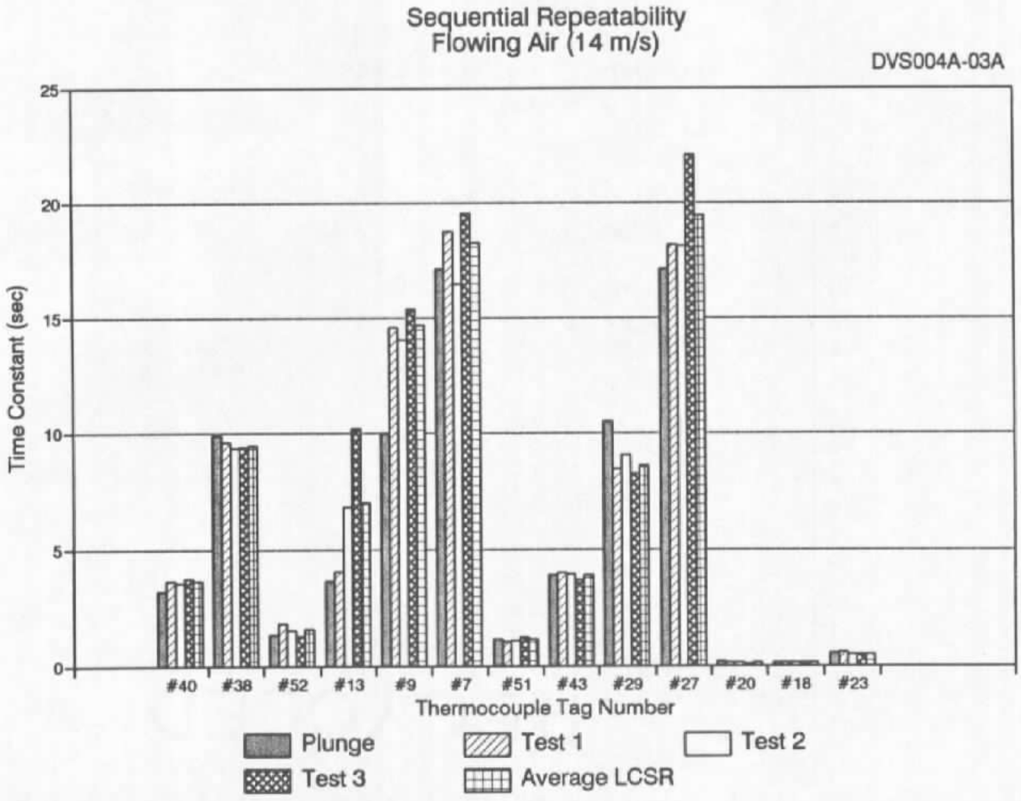


Figure 7.2. Sequential Repeatability (14 m/s Air).

TABLE 7.3

One Week LCSR Repeatability (0.6m/s Water)

Tag #	Plunge (sec)	Sequential (sec)	One Week (sec)
29	1.40	1.10	1.19
27	2.00	1.99	1.91
43	0.37	0.37	0.42
44	2.16	2.19	2.94
46	1.98	2.39	2.65
36	1.43	1.33	0.91
38	1.90	1.98	1.45
40	0.43	0.43	0.47
4	3.06	2.83	2.99
7	2.72	2.96	2.40
9	0.76	0.49	0.41
13	0.27	0.29	0.31

TABLE 7.4

One Week LCSR Repeatability
(14m/s Air)

Tag #	Plunge (sec)	Sequential (sec)	One Week (sec)
13	3.66	7.03	4.41
9	10.03	14.68	10.66
7	17.13	18.27	15.44
51	1.12	1.10	1.25
43	3.88	3.90	4.03
29	10.55	8.61	8.69
27	17.10	19.45	18.16
20	0.16	0.10	0.19
18	0.14	0.12	0.10
23	0.50	0.50	0.45

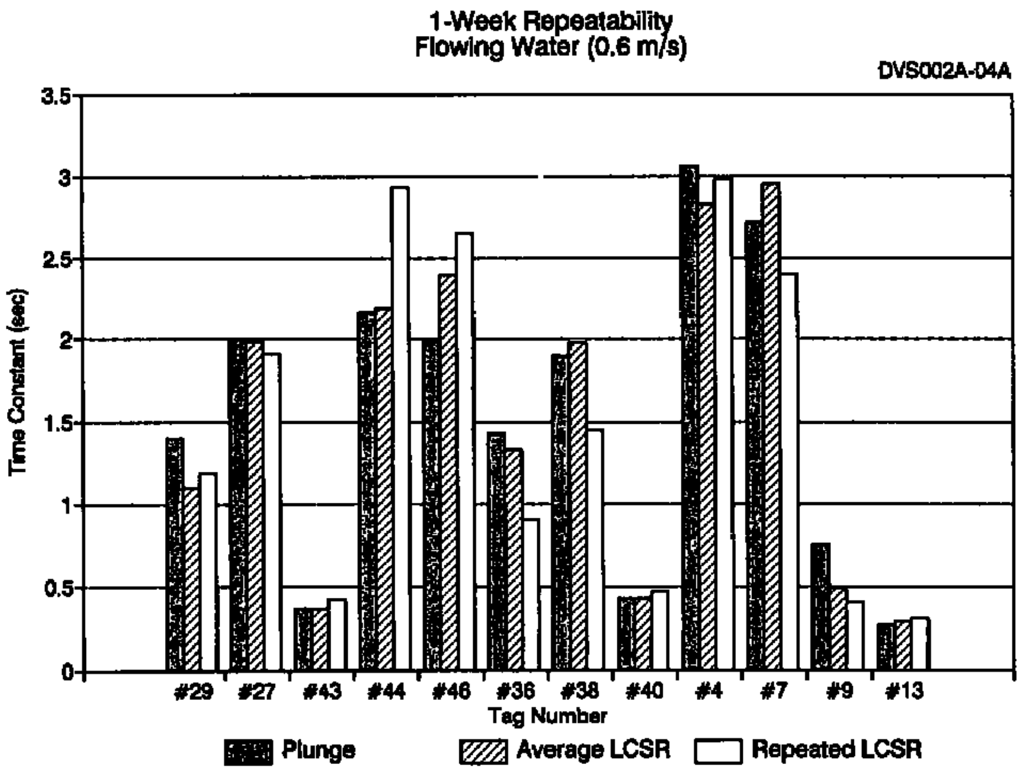


Figure 7.3. One Week Repeatability (0.6 m/s Water).

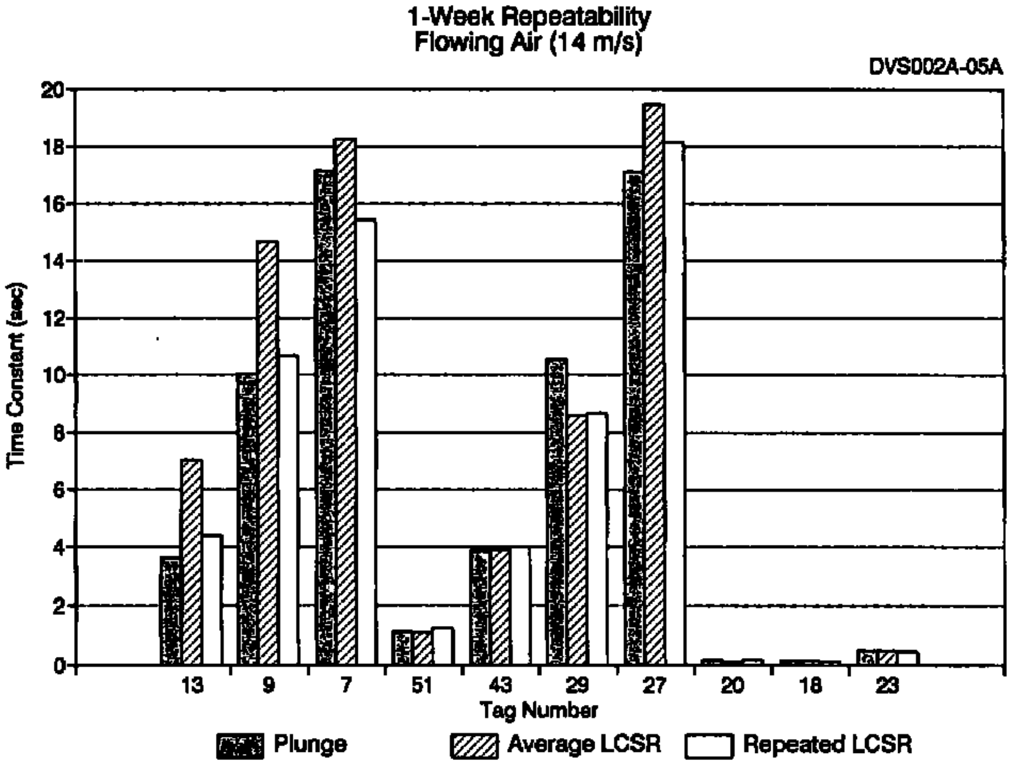


Figure 7.4. One Week Repeatability (14 m/s Air).

TABLE 7.5

Man to Man Repeatability
(0.6 m/s Water)

Tag #	Plunge (sec)	Primary Test (sec)	Repeated Test (sec)
AF#29	1.40	1.10	1.09
AF#43	0.37	0.42	0.44
AF#38	1.90	1.98	1.35
AF#40	0.43	0.43	0.41
AF#09	0.76	0.49	0.74
AF#13	0.27	0.29	0.28
AF#04	3.06	2.83	2.85
AF#07	2.72	2.96	2.26
AF#27	2.00	1.99	2.18
AF#44	2.10	2.19	2.22
AF#36	1.43	1.33	1.14
AF#46	1.98	2.39	1.82

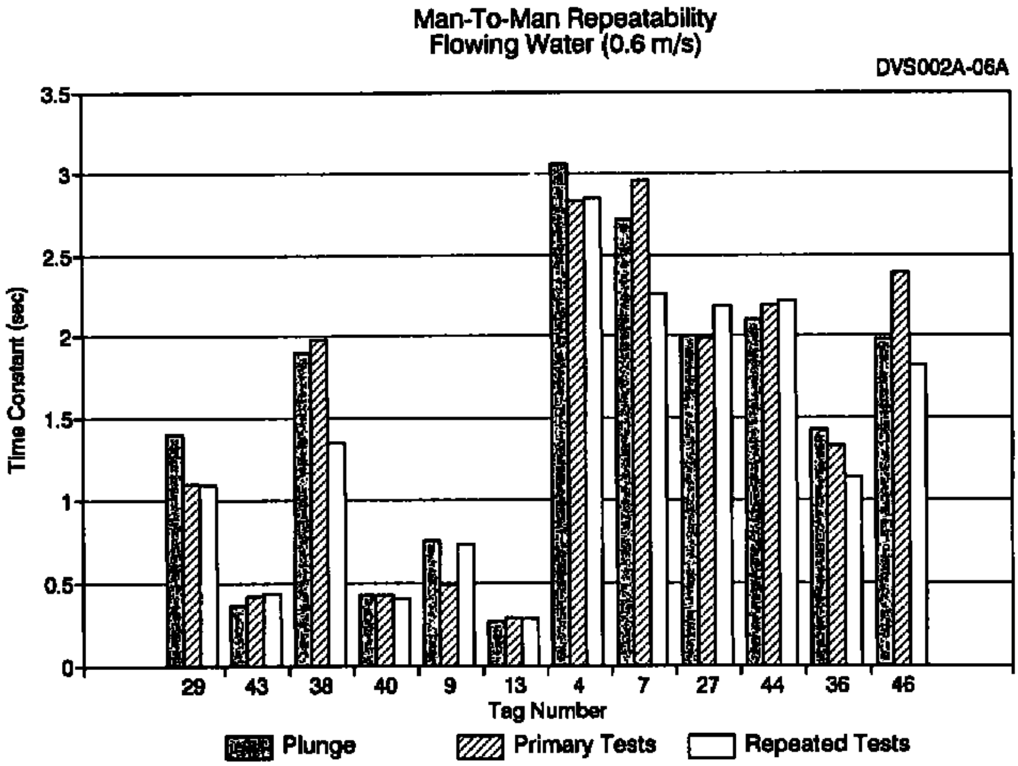


Figure 7.5. Man to Man Repeatability.

8. EFFECTS OF LCSR TESTING ON THERMOCOUPLE EXTENSION WIRE

During LCSR testing of thermocouples, the extension wires are subjected to a measurable amount of Joule heating as the current is applied. Tests were performed to quantify how much of a temperature rise could be expected during typical LCSR testing. This series of tests would also provide limitations of applied current for the LCSR tests.

The experiments were performed using a type "K" thermocouple (AF #01) and a 2 meter length of 20 gage solid extension wire. The tests were divided into two segments. First, the thermocouple and extension wire were heated at varied current levels until a steady state temperature was reached in the wire. The temperature was measured by sealing another thermocouple under the skin of the wire insulation. The results of the tests are shown in Table 8.1 and Figure 8.1, with no damage to the extension wire or insulation noted until approximately 4.0 amperes was used.

In the second series of tests, varied currents were applied to the same thermocouple (AF#01) for a 20 second duration. The starting temperature, temperature after 20 seconds of heating and the maximum temperature reached were measured. The results are shown in Table 8.2 and Figure 8.2. Note that no damage to the wire or insulation occurred until approximately 9 amperes was used.

TABLE 8.1

Final Steady-State Temperature Rise in Thermocouple Extension Wire

Current (Amps)	Start Temperature (°C)	Stop Temperature (°C)	Temperature Increase (°C)
0.5	23.06	23.33	0.27
1.0	23.06	27.78	4.72
2.0	22.78	44.44	21.66
3.0	23.22	75.00	51.78
4.0	22.78	112.78	90.00
5.0	23.89	121.11	97.22

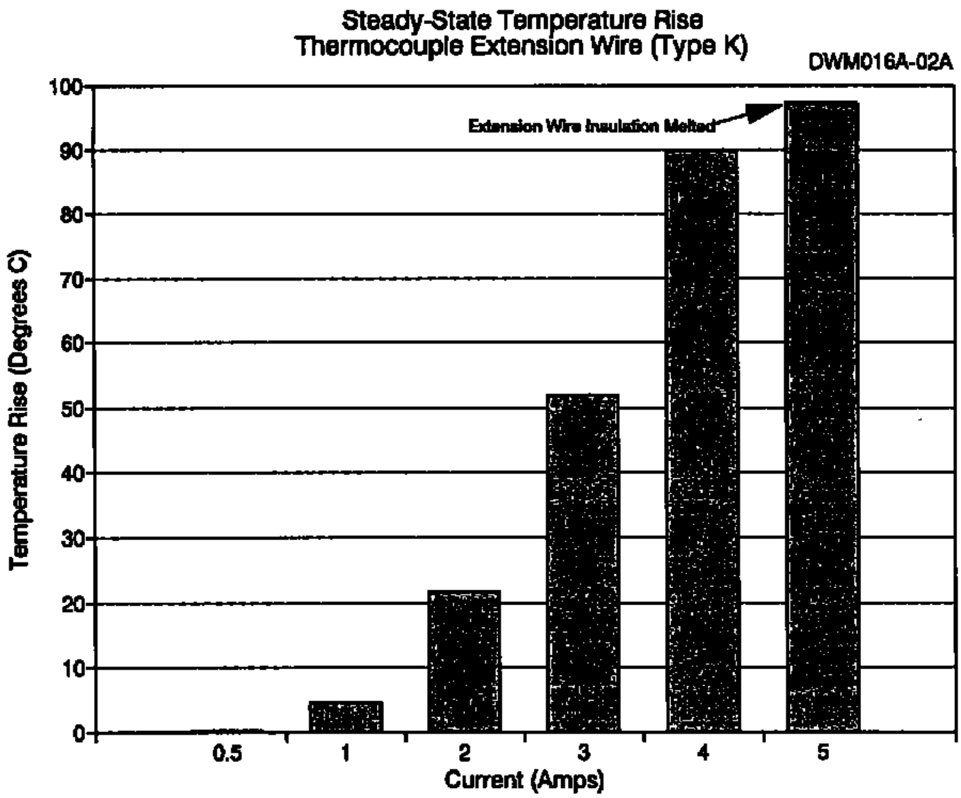


Figure 8.1. Steady-State Temperature Rise in Extension Wire.

TABLE 8.2

Twenty Second Temperature Rise in Thermocouple Extension Wire

Current (AMPs)	Start Temperature (°C)	Stop Temperature (°C)	Maximum Temperature (°C)
0.5	24.78	25.11	25.22
1.0	24.67	25.56	25.56
2.0	24.78	28.33	28.67
3.0	24.89	32.22	32.89
4.0	24.56	36.00	39.33
5.0	24.89	48.33	50.56
6.0	25.56	53.33	57.44
7.0	24.78	66.11	74.00
8.0	25.11	76.67	87.78
9.0	25.67	106.11	108.33

Note: 1. Stop Temperature is the temperature reached after 20 seconds of heating time.

2. Maximum Temperature is the maximum temperature reached after heating for 20 seconds.

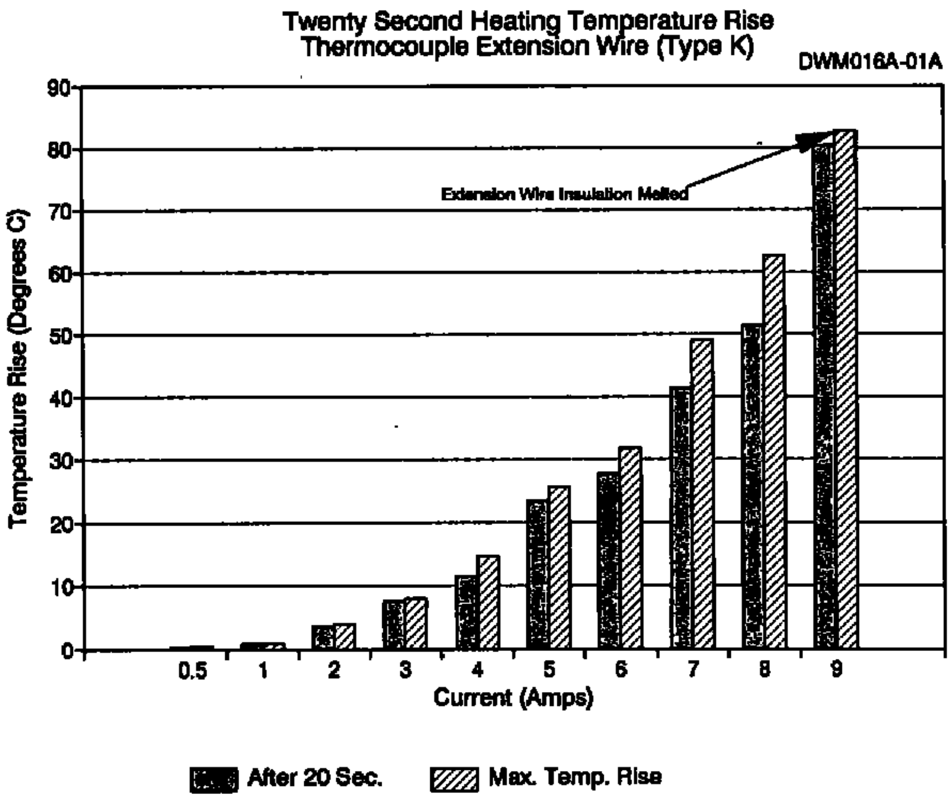


Figure 8.2. Twenty Second Temperature Rise in Extension Wire.

9. SUPPLEMENTAL TESTING OF THERMOCOUPLES

Several additional tests were performed during the project to provide some insight into thermocouple performance and characteristics. Enclosed in this section are results from a series of tests which were performed during the project. They are:

1. Noise Analysis Applications for Thermocouples
2. Thermocouple Inhomogeneity Testing

In addition to the above, Appendix D is a copy of a report sent to the Lockheed Aeronautical Systems Company concerning a field application of the thermocouple LCSR technique.

9.1 Noise Analysis Applications for Thermocouples

The use of noise analysis to determine the response time of pressure sensors has been developed and is used on a frequent basis. Basically, the procedure involves analyzing the random fluctuations (noise) which often occur naturally at the output of a thermocouple while installed in an operating process. These random fluctuations contain information about the dynamics of the process and the sensor. When the bandwidth of the process fluctuations is sufficiently larger than that of the thermocouple, the spectrum of the thermocouple output noise would represent the transfer function of the thermocouple. This transfer function can be used to provide the response time of the thermocouple.

To evaluate the feasibility of using noise analysis for thermocouple response time testing, experiments were performed in air and water. The data acquisition procedure involved the recording of random temperature noise data from a thermocouple's EMF output, removing the electrical DC component, and then amplifying and analyzing the fluctuations. Test data were obtained using a hot air blower (flowing at an estimated 14 m/s) and a multiple input pipe manifold. For the pipe manifold, hot and cold water were used as inputs. The heated water was injected randomly and allowed to mix with cool water to create temperature noise. The results of these tests are shown in Table 9.1 and 9.2. Note that plunge tests were not performed in the hot air flow, but the baseline plunge results at 14 m/s flow were used as an estimate.

TABLE 9.1

Noise Analysis Results Using Hot Air Blower

Tag #	Test #	Plunge Result (sec)	Noise Analysis Result (sec)
AF#20	1	0.16	0.12
AF#20	2	0.16	0.09
AF#20	3	0.16	0.09
AF#20	4	0.16	0.09

TABLE 9.2

Noise Analysis Result Using Pipe Manifold

Tag #	Plunge Result (sec)	Noise Analysis Result (sec)
AF#04	3.70	4.35
AF#20	0.05	0.50

A summary of problems noted during the noise analysis tests are as follows:

1. The recording of a thermocouple's EMF output requires the use of very high amplification (usually > 50,000). Electrical noise from the amplifier will often hide the thermocouple signal.

2. Slower responding thermocouples require data acquisition at low frequencies. The dominating influence at these frequencies is the high pass filter (used to remove the DC component of the signal) and not the thermocouple output.

Example noise analysis Power Spectral Density (PSD) plots are shown in Figures 9.1.1 and 9.1.2.

9.2 Thermocouple Inhomogeneity Testing

Inhomogeneities present in thermocouples may cause critical temperature measurement errors when they are located within a thermal gradient. Simple tests were performed to display how an inhomogeneity in a thermocouple could be detected. To accomplish this, a type "K" thermocouple was constructed as shown in Figure 9.2.1. An inhomogeneity was introduced in one lead of the thermocouple by cutting the lead wire and re-soldering it back together. The test fixture was then connected to an amplifier and strip chart recorder to monitor its output during testing. The thermocouple's measuring and reference junctions were inserted into a bath of water while a localized temperature gradient was passed along the wire. Figures 9.2.2 and 9.2.3 are examples of the output from the thermocouple during the test. Note that the spikes which are present indicate where the temperature gradient passed over the inhomogeneity.

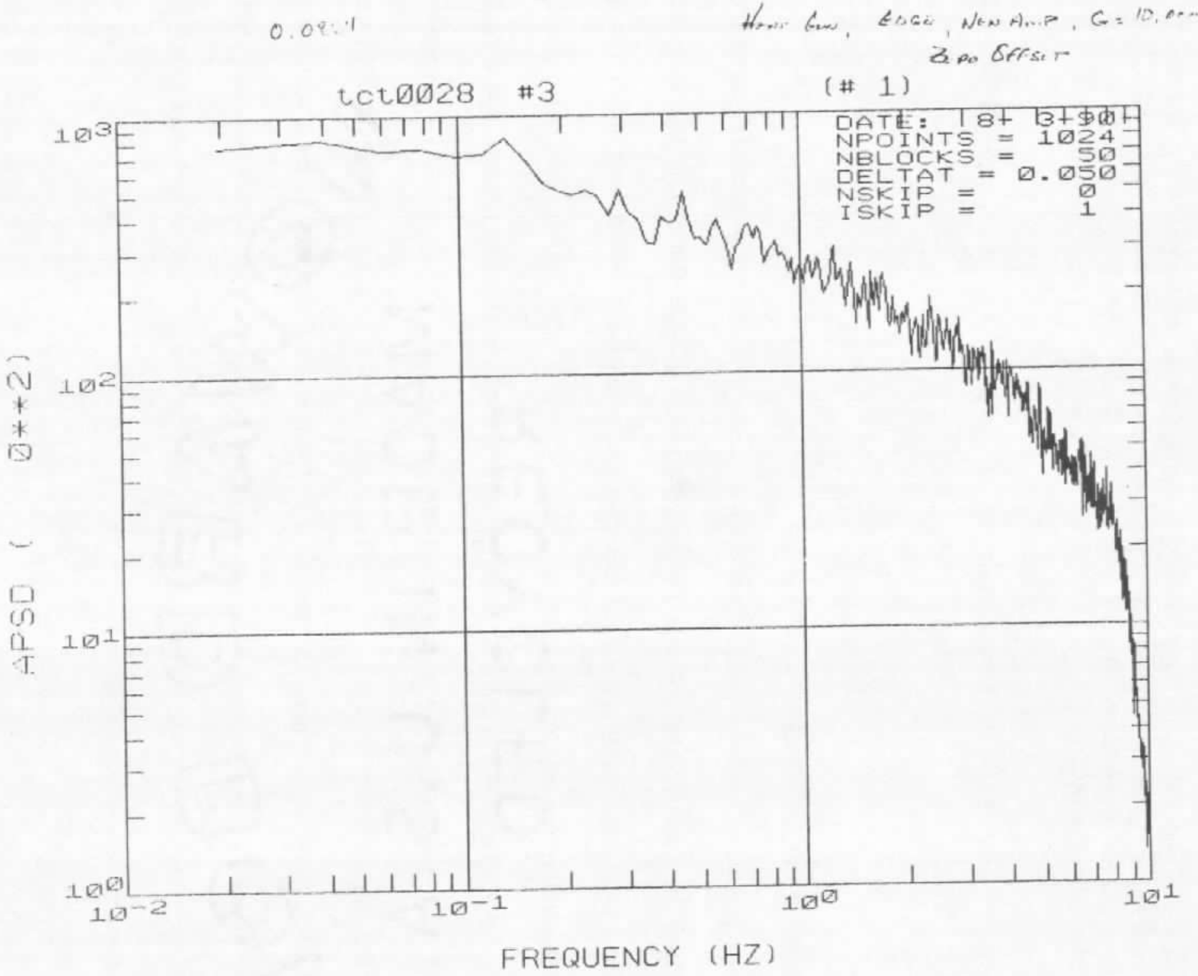


Figure 9.1.1. PSD for Thermocouple #AF20 Using Heat Gun.

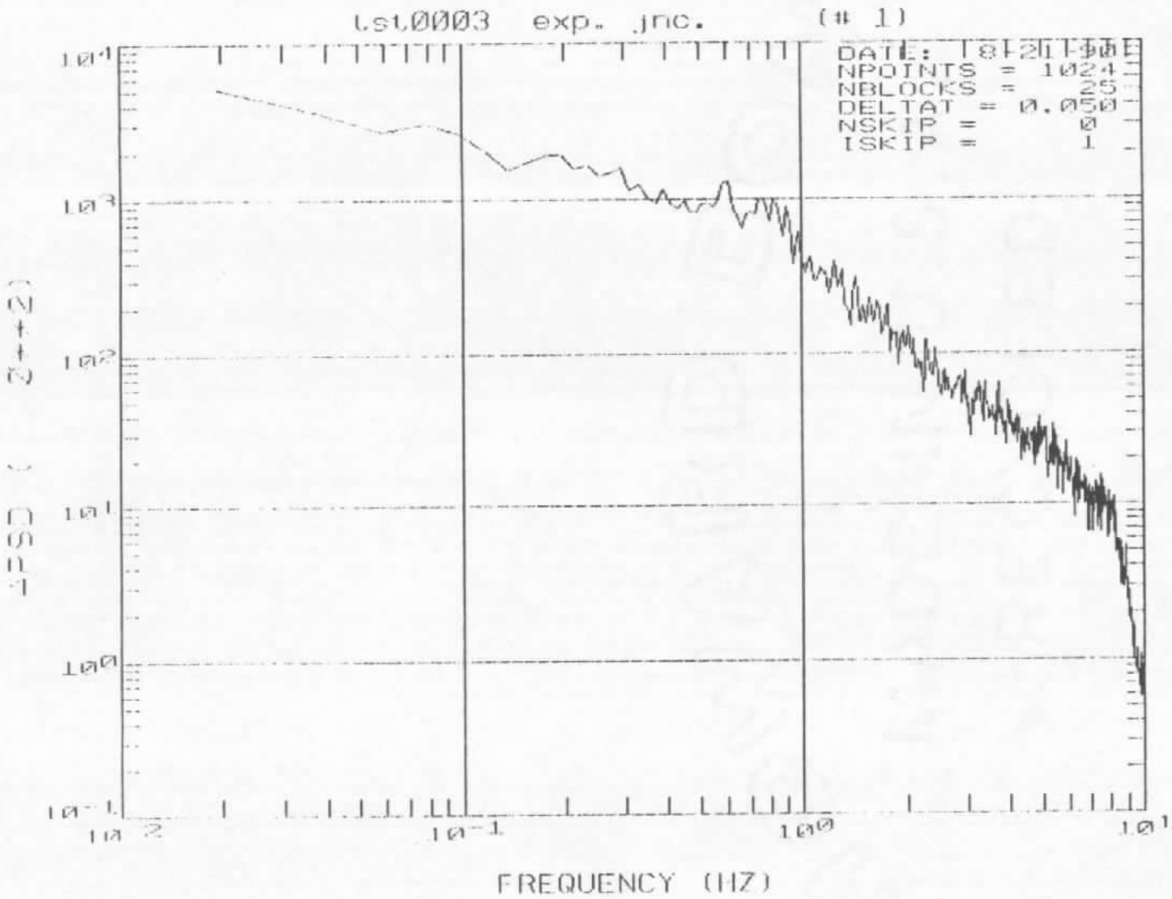


Figure 9.1.2. PSD for Thermocouple #AF20 Using Pipe Manifold.

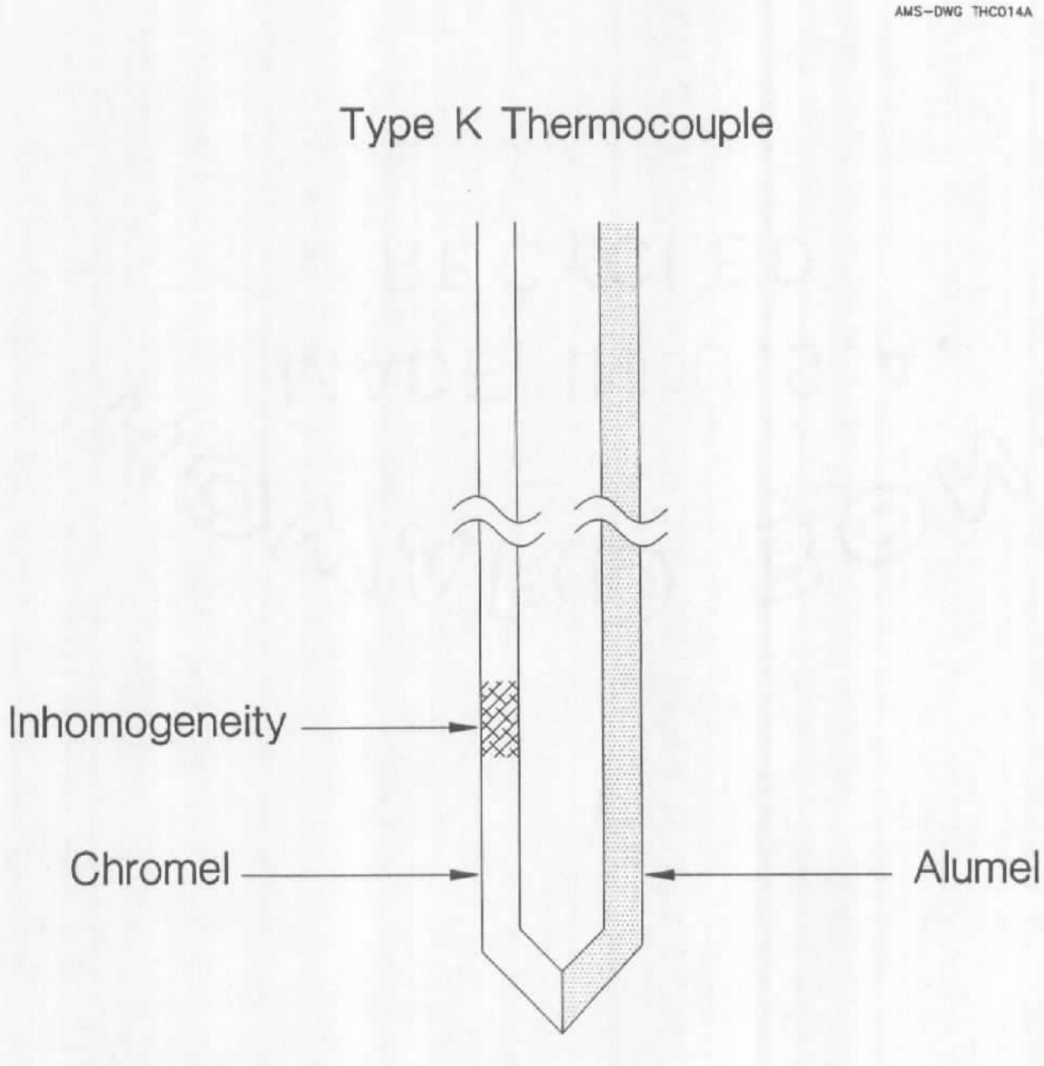


Figure 9.2.1. Inhomogeneity Test Thermocouple.

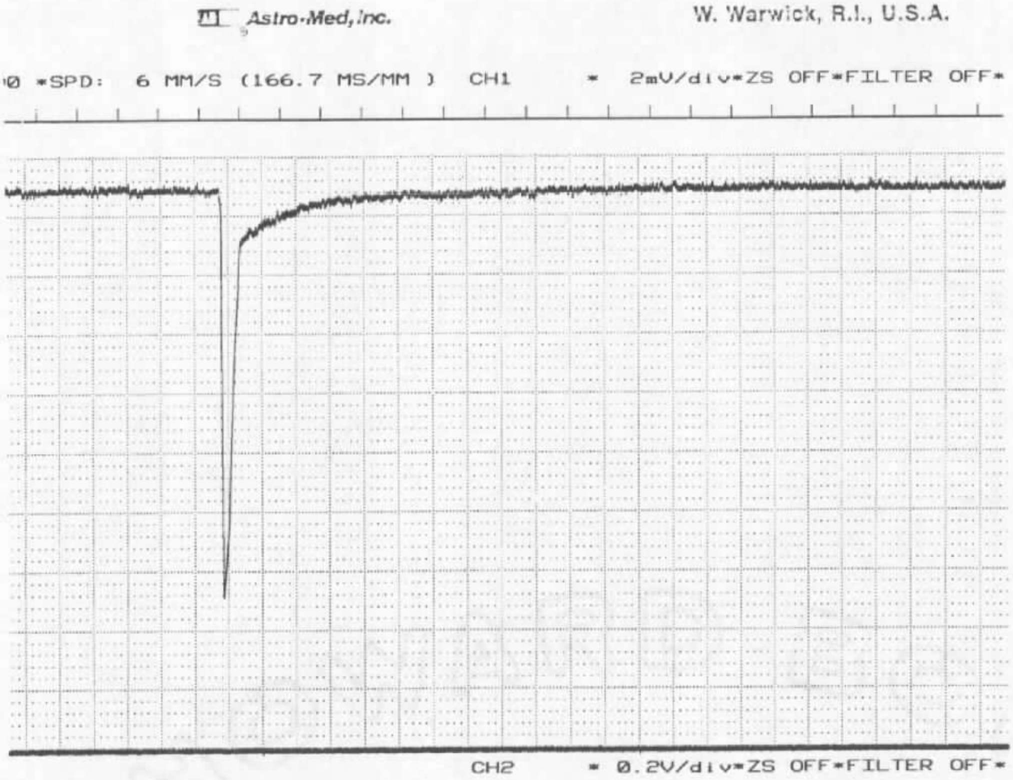


Figure 9.2.2. Inhomogeneity Test Chart Recording (Amplifier Gain Set at 1000).

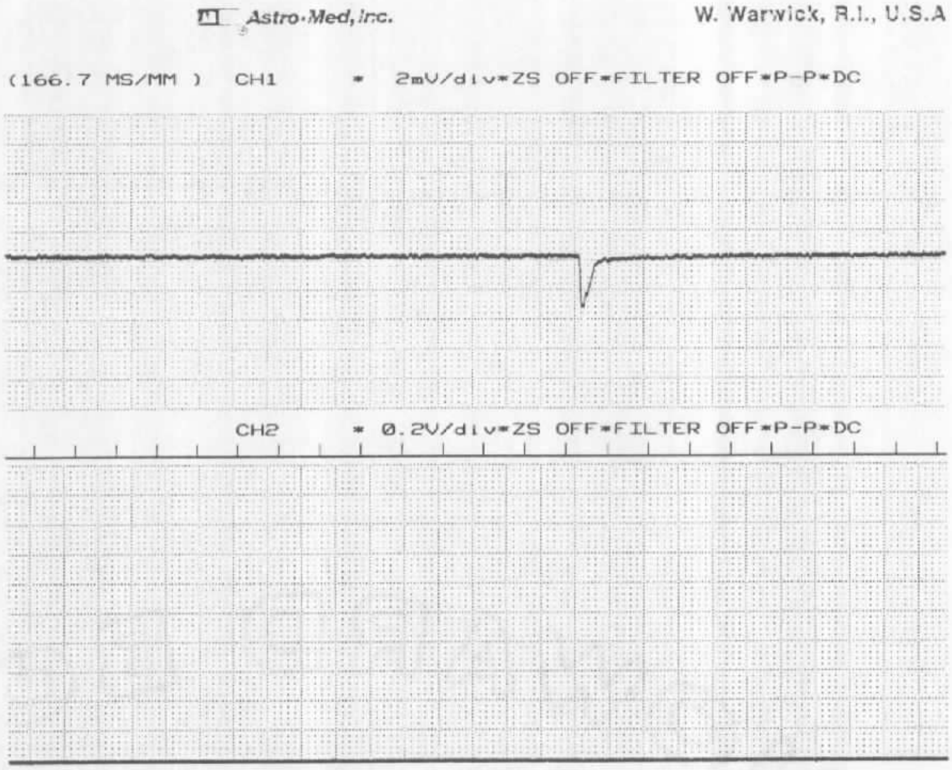


Figure 9.2.3. Inhomogeneity Test Chart Recording (Amplifier Gain Set at 500).

10. THERMOCOUPLE CALIBRATION

A small portion of the research performed in this project was devoted to thermocouple calibration. An overview of the results of the three major tasks completed (calibration repeatability, effects of LCSR on calibration, and high temperature calibration) will be presented.

10.1 Calibration Method

Table 10.1 lists the configuration of the 20 thermocouples used. Note that these thermocouples were different from those used for the primary LCSR research. All thermocouples were approximately 31cm long, sheathed in stainless steel, and had ungrounded junctions. The method used for the calibrations was a variation of Method B described in ASTM Standard E 220. In order to improve temperature stability, a cylindrical copper block was inserted into the oil bath. The block has a center hole and six equidistant holes drilled in one end. A Standard Platinum Resistance Thermometer (SPRT) was inserted into the center hole with its leads connected to a digital multimeter (DMM) in a 4-wire ohms configuration. Each thermocouple was connected to a different channel of a multiplexer. The outputs of the multiplexer were connected to a second DMM and the entire data acquisition process was automated using the IEEE-488 protocol.

Due to the short length of the test thermocouples, it was physically impossible to immerse the ends of the thermocouple in an ice point reference junction. As a result, extension wires were used. The reference junction ends of the extension wires were soldered to copper wires which were then connected to the various multiplexer channels. The soldered junction was then encased in heat shrink tubing to allow direct immersion of the junction into the ice bath.

TABLE 10.1

Thermocouple Calibration List

Tag #	Type	Grade	Sheath Diam
AFC #01	K	std.	6 mm
AFC #02	K	std.	5 mm
AFC #03	K	std.	3 mm
AFC #04	K	std.	2 mm
AFC #05	E	std.	6 mm
AFC #06	E	std.	5 mm
AFC #07	E	std.	3 mm
AFC #08	E	std.	2 mm
AFC #09	J	std.	6 mm
AFC #10	J	std.	5 mm
AFC #11	J	std.	3 mm
AFC #12	J	std.	2 mm
AFC #13	K	unknown	3 mm
AFC #14	J	unknown	3 mm
AFC #15	K	spl.	3 mm
AFC #16	E	spl.	3 mm
AFC #17	J	spl.	3 mm
AFC #18	K	spl.	3 mm
AFC #19	E	spl.	3 mm
AFC #20	J	spl.	3 mm

10.2 Thermocouple Calibration Repeatability

Figures 10.2.1 through 10.2.6 show typical calibration results for the thermocouples. Note that the results are expressed as differences from standard thermocouple reference tables. The first three calibrations were performed on the thermocouples in the "as-received" condition with no prior testing. Using these three calibrations, it is shown in the figures that the calibration repeatability ranges from approximately 0.1°C to 0.5°C depending on the particular thermocouple. Note that Figures 10.2.4 through 10.2.6 are for special grade thermocouples in lieu of standard grade.

10.3 Effects of LCSR on Thermocouple Calibration

Since the LCSR method is being used to perform in-situ response time testing, it was important to determine its impact on the accuracy of thermocouple calibration. The fourth calibration was performed after LCSR testing had been done on all twenty thermocouples. The LCSR tests were accomplished using nominal current and heating times in accordance with procedures used for all the LCSR research performed previous to these tests. Figures 10.2.1 through 10.2.6 provide typical results, and also show the fourth calibration plotted with the other three calibrations. No noticeable effects of LCSR on the calibrations were detected in any of the thermocouples tested.

10.4 High Temperature Thermocouple Calibration

Six thermocouples were calibrated at a relatively high temperature (400°C), and results compared to a standard type "S" thermocouple's measurements. Figures 10.4.1 through 10.4.6 show the results of these tests. These figures represent differences in calibration for each thermocouple tested at each temperature, including the high temperature point.

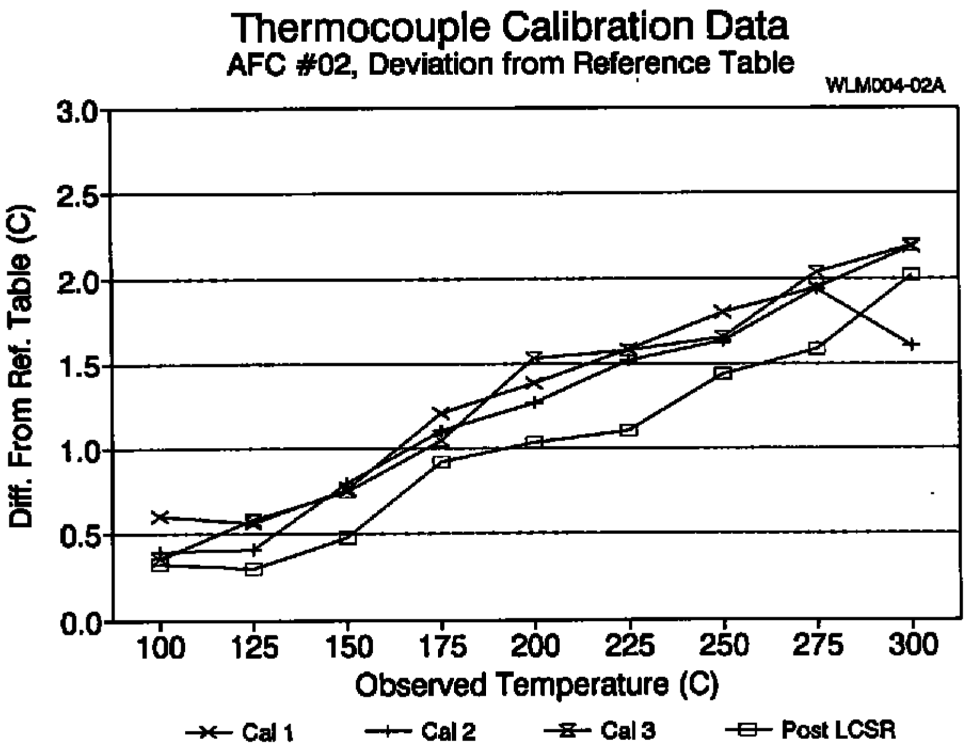


Figure 10.2.1. Thermocouple Calibration AFC#02 (0-300°C).

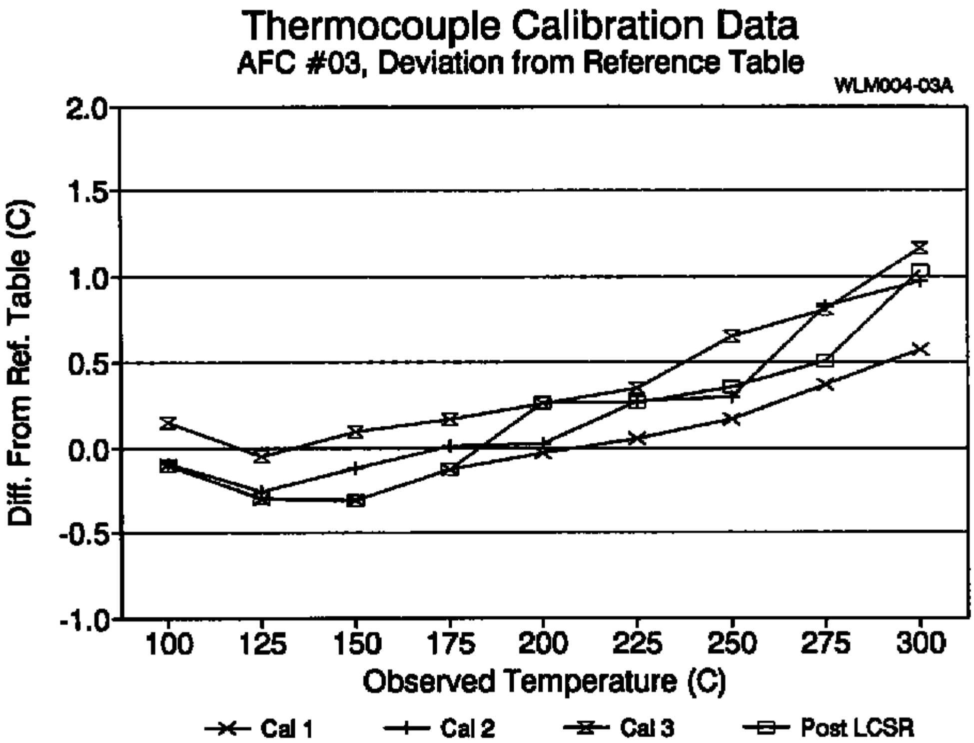


Figure 10.2.2. Thermocouple Calibration AFC#03 (0-300°C).

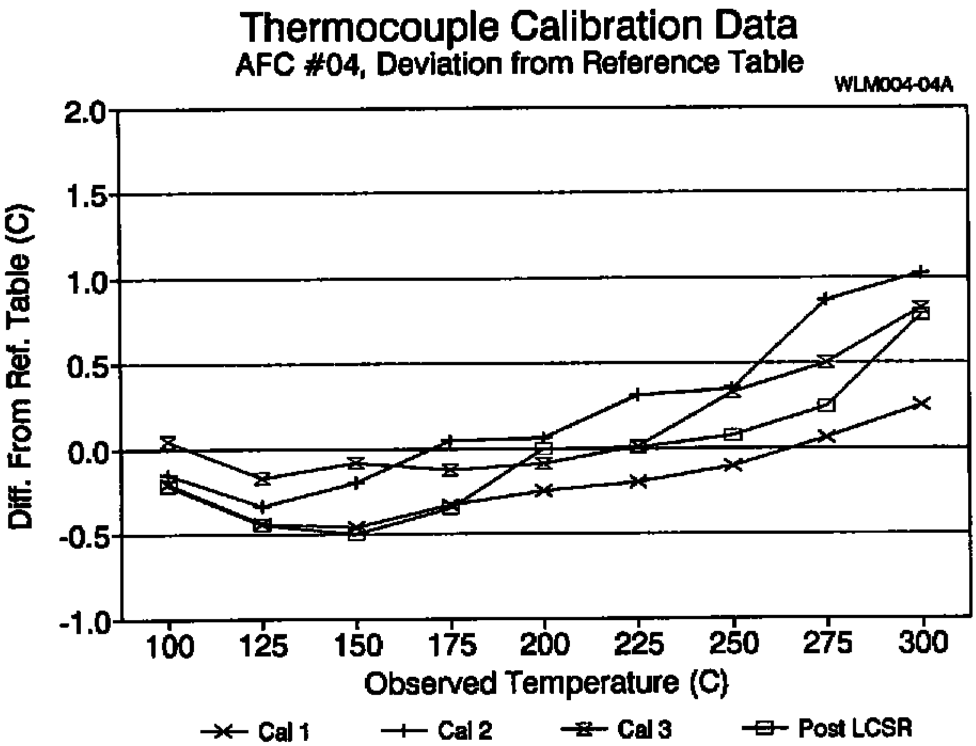


Figure 10.2.3. Thermocouple Calibration AFC#04 (0-300°C).

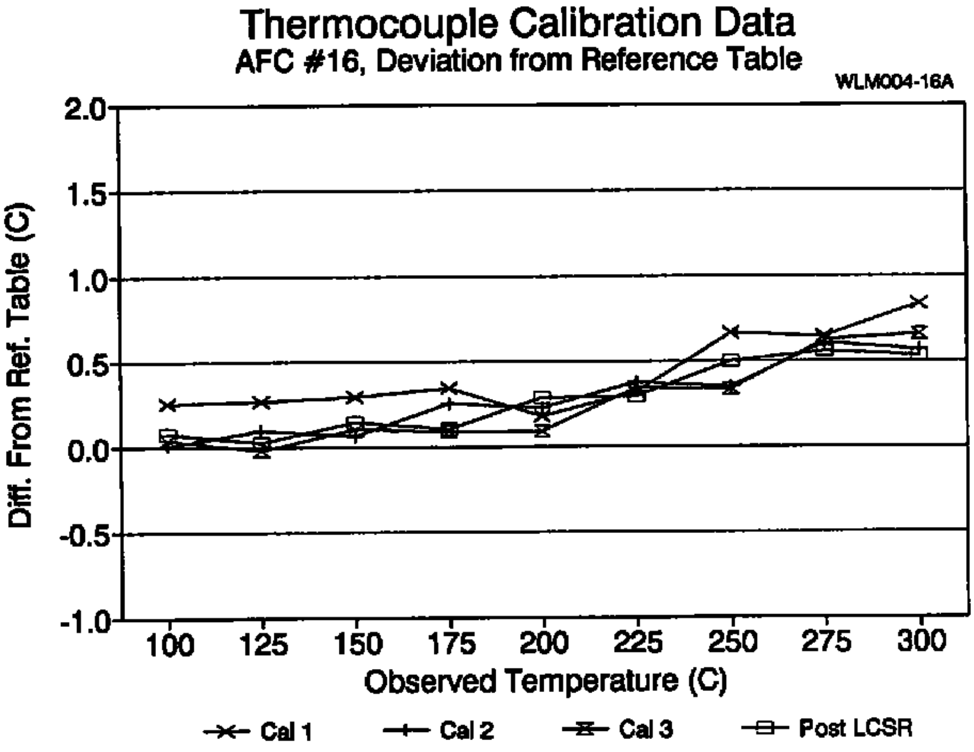


Figure 10.2.4. Thermocouple Calibration AFC#16 (0-300°C).

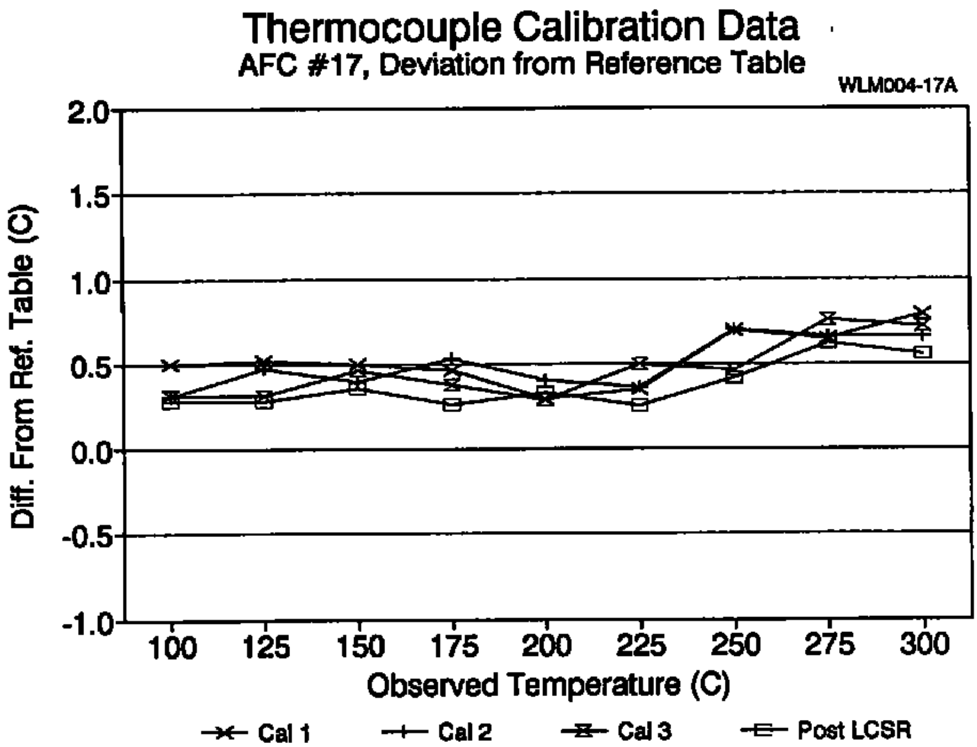


Figure 10.2.5. Thermocouple Calibration AFC#17 (0-300°C).

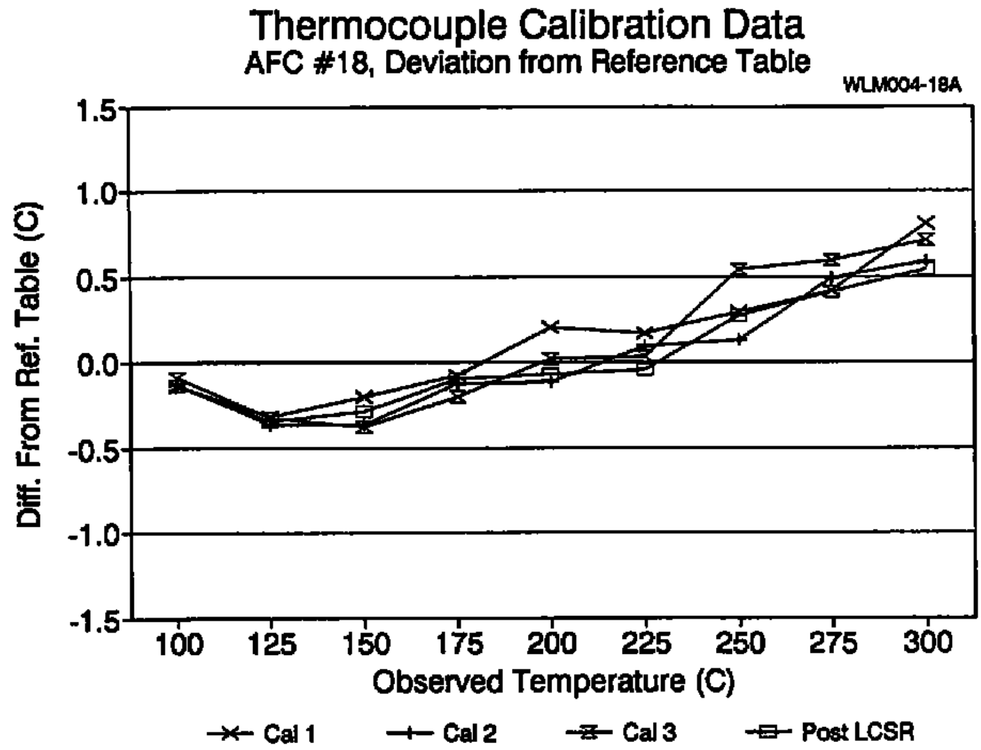


Figure 10.2.6. Thermocouple Calibration AFC#18 (0-300°C).

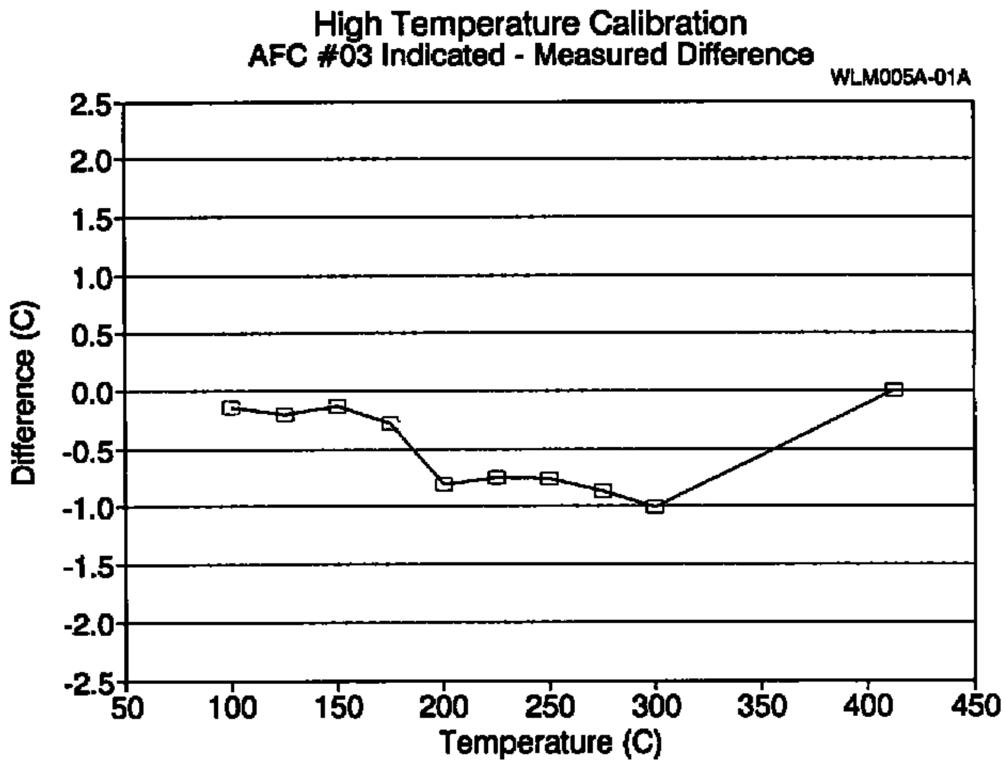


Figure 10.4.1. High Temperature Calibration (AFC#03, 0-400°C).

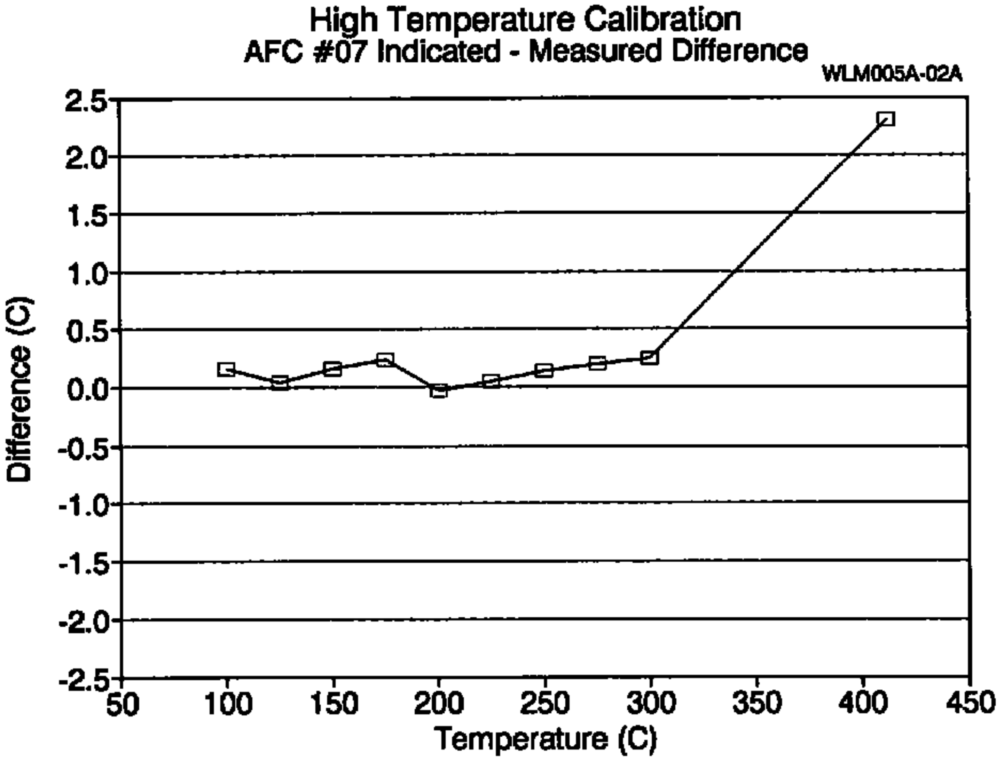


Figure 10.4.2. High Temperature Calibration (AFC#07, 0-400°C).

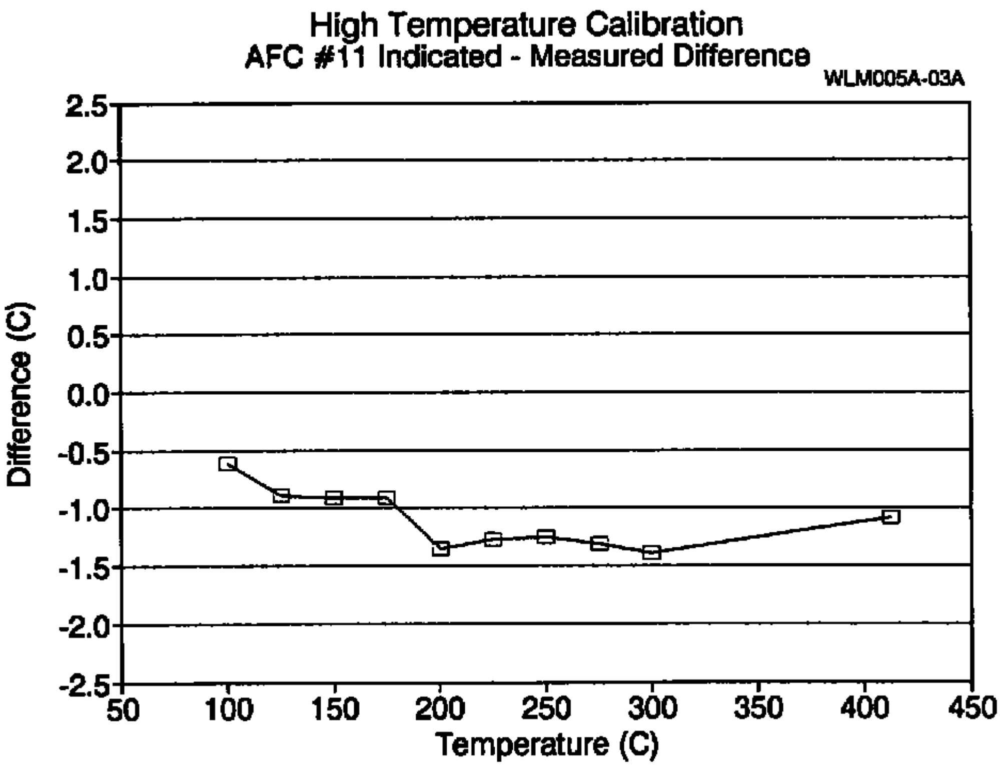


Figure 10.4.3. High Temperature Calibration (AFC#11, 0-400°C)

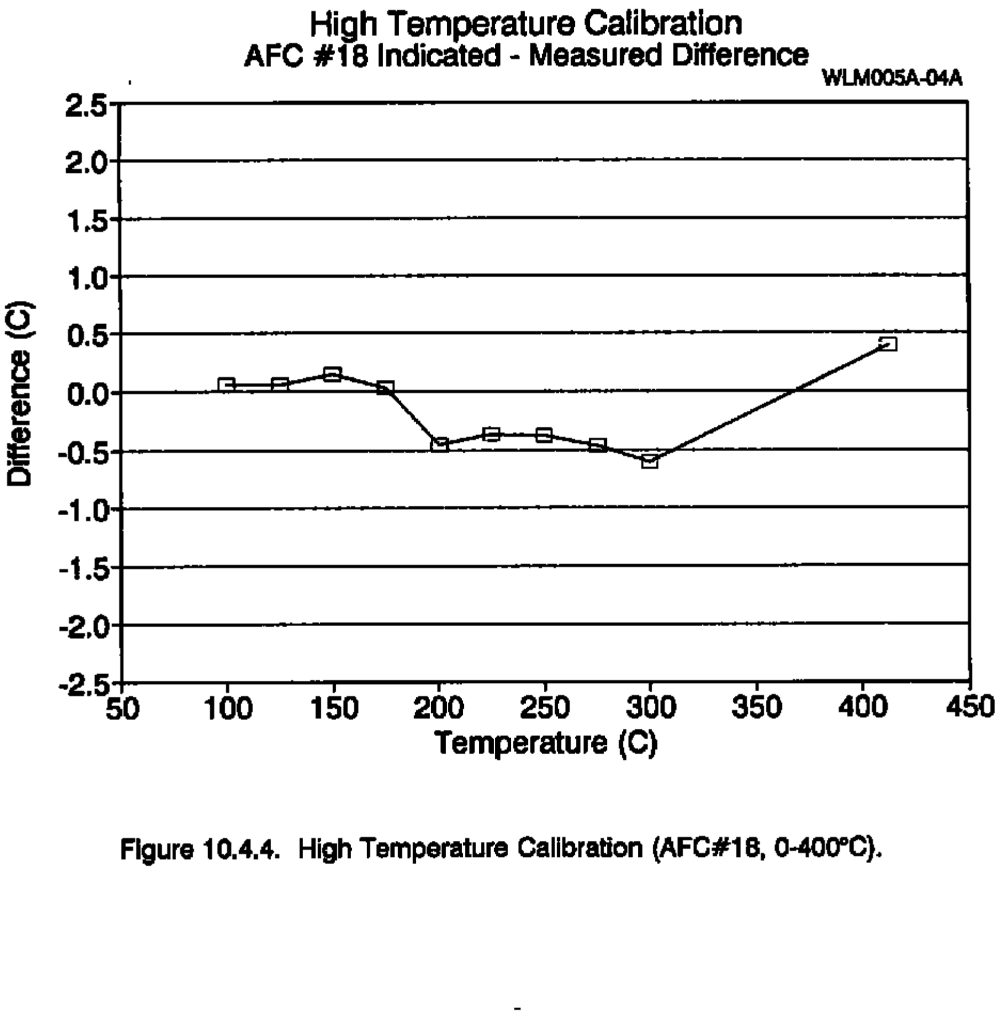


Figure 10.4.4. High Temperature Calibration (AFC#18, 0-400°C).

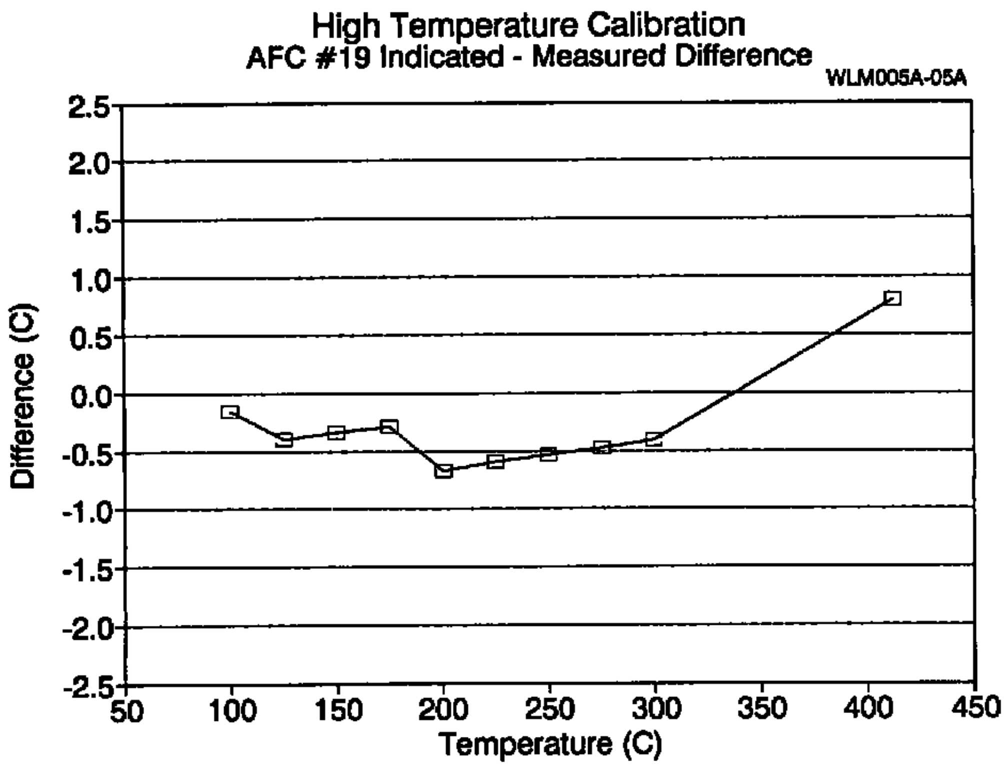


Figure 10.4.5. High Temperature Calibration (AFC#19 0-400°C).

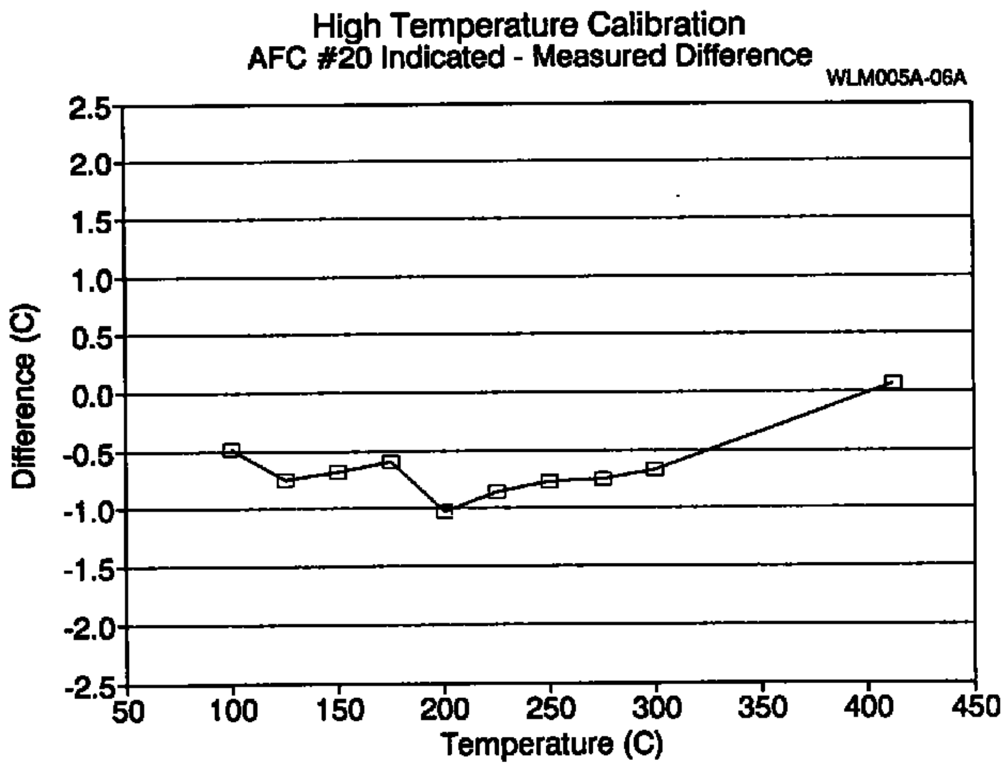


Figure 10.4.6. High Temperature Calibration (AFC#20, 0-400°C).

11. DYNAMIC MODELING OF THERMOCOUPLES

A simplified finite difference numerical model describing the dynamic heat transfer response of a bare junction thermocouple to step changes in temperature was developed as part of this project. The model was designed to replicate both plunge and LCSR tests. Although the model is not intended to be used in place of these tests, it can be used for interpolation or extrapolation for conditions not tested (i.e., different wire sizes, flow conditions, thermocouple types, etc). A detailed description of the model is provided below. A listing of the source code is provided in Appendix B.

11.1 Thermocouple Model Background Theory

The model was developed using a lumped capacity heat transfer analysis in the radial dimension, which assumes no radial temperature variation in the thermocouple wire or in the junction. Although this is an idealized assumption, the small size of the thermocouple wire and the relatively high thermal conductivity make this an acceptable choice for exposed junction thermocouples, but a poor choice for grounded or sheathed thermocouples.

The mathematical formulation involves one dimensional, unsteady state heat transfer with heat conduction along the wires. Note that radiation heat transfer has been neglected since this would affect results only if the convection heat transfer coefficient is very low. The model becomes two dimensional in regions where the wire is insulated, but only to the extent that the wire may have a different temperature than the surrounding insulation. Like the wire, the insulation temperature is assumed to vary only along its length. The wire and the insulation can be divided into 200 separate sub-lengths, where each sub-length is represented by a node at its

center. The temperature is then assumed to be constant over each sub-length. Figure 11.1.1 illustrates the thermocouple as represented by nodes in the analytical model. The two wires are identified as wire "A" and wire "B" in order to allow for separate property inputs such as thermal conductivity, specific heat, density and electrical resistivity for each wire material. Six different areas are identified in the figure. The heat transfer equations will be different for each specific area; however, within an area the form of the equations will be identical.

As shown in the figure, the six identified areas of the thermocouple are:

1. Measuring Junction, where wire properties are assumed to be the average of wires "A" and "B" and the size may be the same as the wire diameter or a larger spherical shape.

2. Sub-Region 1, the bare wire adjacent to the measurement junction. The node spacing is smallest in this region where the results most critically affect the time constant.

3. Sub-Region 2, the insulated wire inside the test environment.

4. Sub-Region 3, the insulated wire outside the test environment.

5. Sub-Region 4, the bare wire adjacent to the reference junction.

6. The reference junction, where the wire attaches to the test instrument.

The analysis procedure for Sub-Regions 1 and 4 are identical except the convection coefficient is different. The same conclusion holds for Sub-Regions 2 and 3.

11.2 Solution Technique

The equations for each area were developed in finite difference form and solved by an explicit technique. The model's equations are explicit because all unknown nodal temperatures for the new time are determined exclusively from the known nodal temperatures at the previous

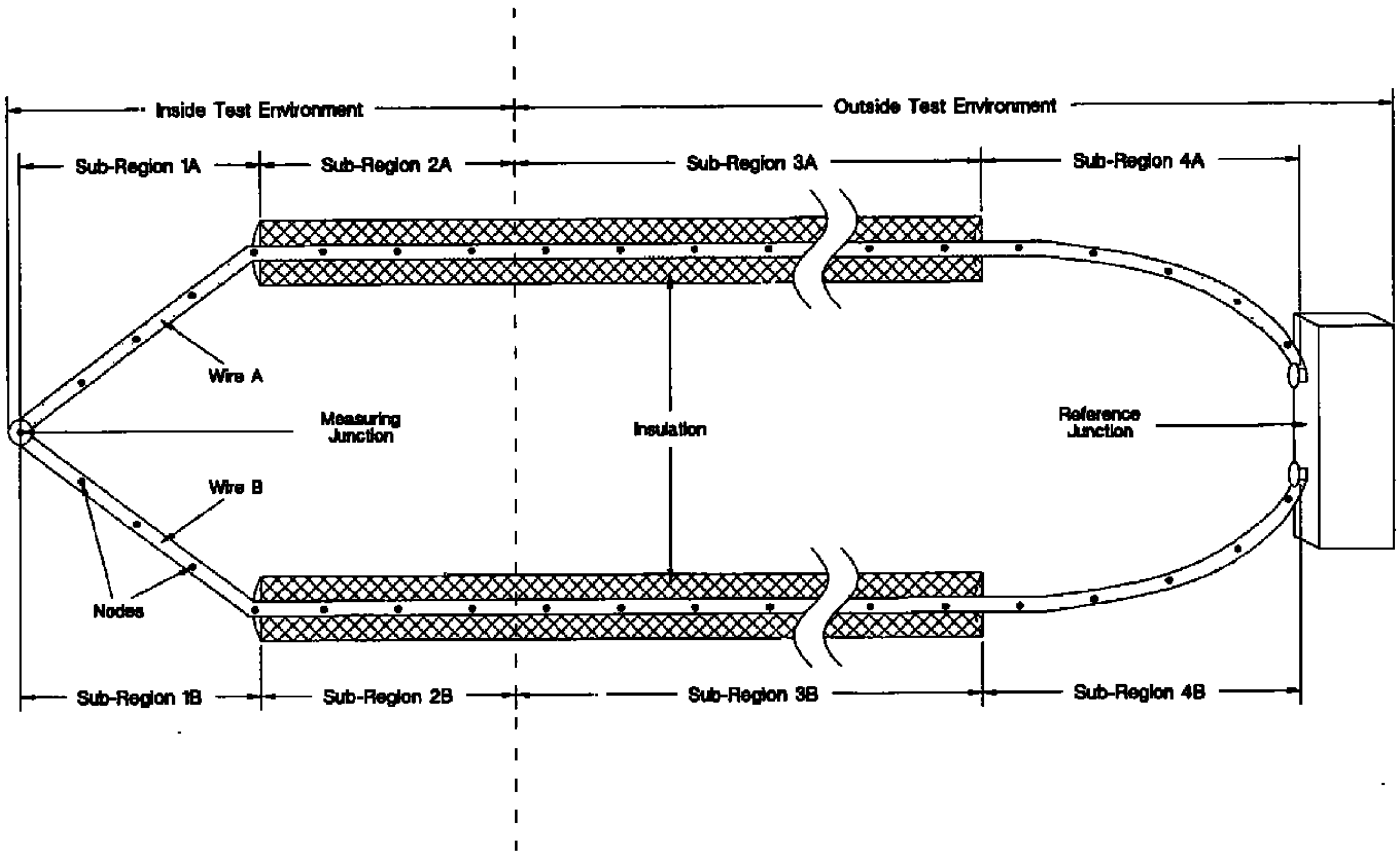


Figure 11.1.1 Thermocouple Model Diagram

time. Hence calculation of the unknown temperature is straight forward. Since the temperature of each interior node is known at time = 0 (from prescribed initial conditions), the calculation begins at time = Dt where Dt is the selected time increment. With temperatures known at every node for time = Dt, the equations are then applied again at each node to determine temperatures at time = 2Dt in terms of the temperatures at time = Dt.

The accuracy of this technique may be improved by decreasing the time increment and the length increment between the nodes. Of course the smaller increments require more nodes and more calculations per time increment so that computing time may be significantly increased. The choice of length increment is usually a compromise between computation time and accuracy.

An undesirable feature of the explicit method is that it is not unconditionally stable. In a transient problem (such as the model), the solution for the nodal temperatures should continuously approach final (steady-state) values with increasing time. However, with the explicit method, the solution may be characterized by numerically induced oscillations which are non-causal. The oscillations may become unstable, forcing the solution to diverge from actual final conditions. To prevent such erroneous results, the prescribed value of Dt must be maintained at small values, which depends on the nodal length increment and other system parameters. This dependence is known as the stability criterion.

11.3 Thermocouple Model Simulation Algorithm

The numerical model can simulate either a plunge or LCSR test. Initially, a uniform value is assumed for all temperatures. To simulate a plunge test, the measuring junction and

Sub-regions 1 and 2 are instantaneously exposed to a surrounding fluid of uniform temperature different from the initial temperature of the thermocouple. Using a preselected time increment, the temperature at each node is calculated at the end of the time increment in terms of surrounding temperatures at the beginning of the time increment. The time is incremented once again and all temperatures recalculated in terms of surrounding temperatures at the beginning of the current time increment. When using the explicit scheme, a time increment of 0.01 seconds appears to produce stable results for all cases studied.

To simulate an LCSR test, the measuring junction and subregions 1 and 2 of the thermocouple are initially assumed to be at the uniform temperature of the test environment. Sub-regions 3 and 4 and the reference junction are at room temperature. At time equal to zero, electric power generation is assumed to occur throughout the wires. At the end of each time increment, the temperatures are recalculated at each node and the procedure continued until the current is shut off. The electric current in amps and time of application are inputs to the program. After the current is shut off, the measuring junction and wire are cooled by convection in the test environment and the solution continues with the power generation terms set equal to zero.

In both plunge and LCSR tests, the time constant is determined by curve fitting the parameter $\frac{(T_J - T_F)}{(T_{J1} - T_F)}$ versus time on semi-logarithmic coordinates

where

T_J is the measuring junction temperature
T_{J1} is the initial measuring junction temperature
and T_F is the temperature of the test environment

11.4 Heat Transfer Equations

The equations used for the development of the model are basic heat transfer relations. The terms (and associated units) used throughout these equations are declared below:

1. "Q" (W): Heat Transfer Rate
2. "K" (W/m °C): Thermal Conductivity
3. "A" (m^2): Area Normal to the Direction of Heat Flow
4. "h" (W/m^2 °C): Convection Heat Transfer Coefficient
5. "I" (A) : Current
6. "R" (Ω): Resistance
7. ρ (Kg/m^3): Density
8. V (m^3): Volume
9. C_p (J/Kg °C): Specific Heat

The basic equations used were:

1. Conduction along the wire

$$Q = -KA\frac{dT}{dX}$$

where dT is the temperature difference between any two adjacent nodes along the wire, spaced dx apart

2. Convection from the wire to the surrounding fluid

$$Q = hA\Delta T$$

where ΔT is the temperature difference between the wire and surrounding fluid temperature

3. Conduction heat transfer between the wire and insulation

$$Q = -KA\frac{dT}{dX}$$

where dT is the insulation temperature minus the wire temperature, dX is 1/2 the insulation thickness and K is thermal conductivity of the insulation

4. Convection heat transfer between the outer surface of the insulation and the surrounding fluid.

   $Q = h\,A\,\Delta T$

5. Energy generated due to electrical current

   $Q_{Gen} = I^2 R$

The development of the equations for each area is shown below. Drawings of the model relationships are shown in Figures 11.4.1 through 11.4.4.

1. Measuring Junction

The equations are based on an energy balance using the First Law of Thermodynamics for each node, where the net effect of the rate of heat transfer to or from the node by conduction along the wire, convection with the surrounding fluid, and heat generation within the node due to an electrical current may produce a change in the measuring junction temperature with time. Junction properties are averaged between the two wire materials at the measuring junction. The energy balance is as follows:

$$Q_{B\to J} + Q_{A\to J} + Q_{FLUID\to J} + Q_{Gen} = \frac{dE}{dt}$$

Where $Q_{B\to J}$ is the rate of heat conduction along the wire from node B to node J and dE/dt is the time rate of energy change of node J.

Note the following:

$$Q_{B\to J} = \frac{K_B A\,(T_B - T_J)}{L}$$

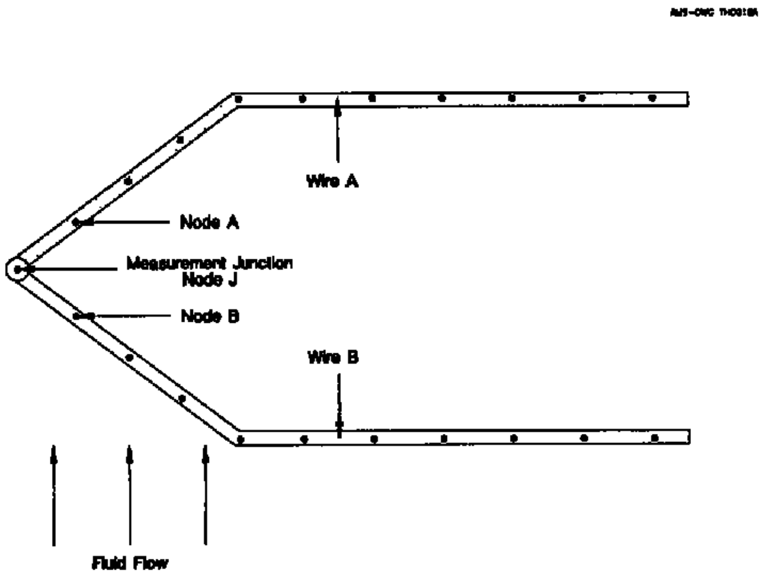


Figure 11.4.1. Model Relationship (Measuring Junction)

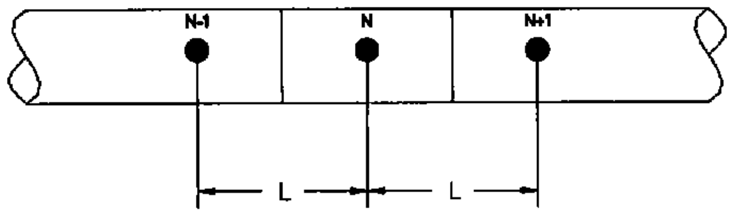


Figure 11.4.2. Model Relationship (Bare Wire)

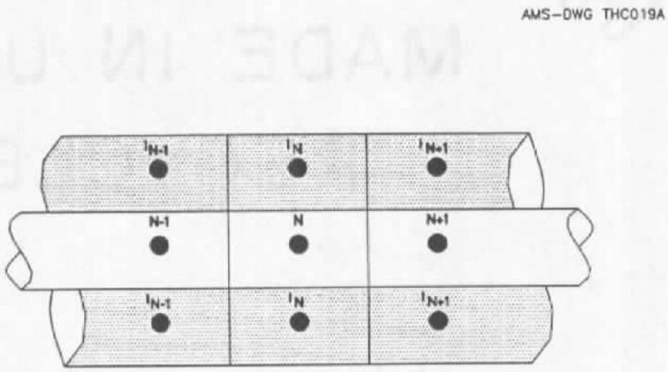


Figure 11.4.3. Model Relationship (Insulated Wire)

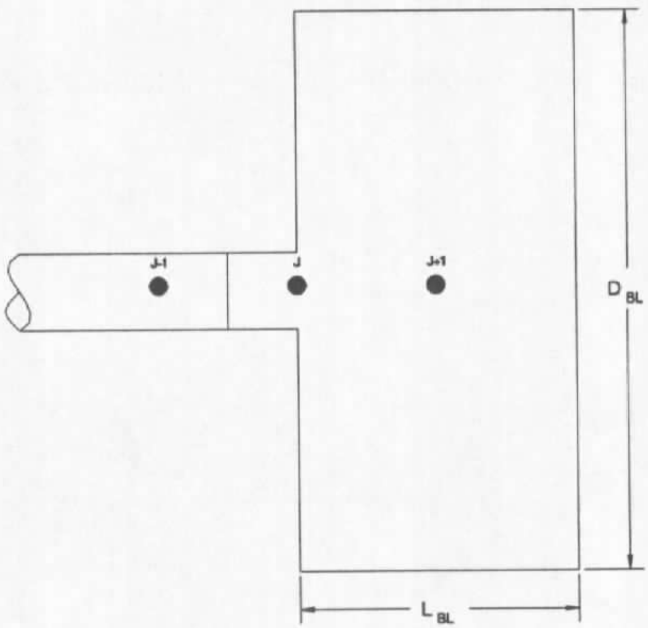


Figure 11.4.4. Model Relationship (Reference Junction)

$$Q_{A \to J} = \frac{K_A A \,(T_A - T_J)}{L}$$

$$Q_{FLUID \to J} = hA \;(T_F - T_J)$$

$$Q_{Gen} = I^2 R$$

$$\frac{dE}{dT} \doteq \frac{\rho \, V \, C_p \,(T_{J1} - T_J)}{\Delta t}$$

substituting into the energy balance equation and solving for T_{J1} gives:

$$T_{J1} = T_J + [C1\;(T_A - T_J) + C2\;(T_B - T_J) + C3\;Q_{Gen} + C4\;(T_F - T_J)]\;\Delta t$$

Where all quantities on the right side are evaluated at the previous time when they are known, and C1 through C4 are known parameters. Note that T_{J1} is the temperature at node J Δt seconds after the temperature at node J is equal to T_J, and T_F is the fluid temperature.

2. **Energy balance for nodes in the bare wire**

$$Q_{N-1 \to N} + Q_{N+1 \to N} + Q_{F \to N} + Q_{Gen} = \frac{dE}{dt}$$

where

$$Q_{N-1 \to N} = \frac{K\,A\,(T_{N-1} - T_N)}{L}$$

$$Q_{N+1 \to N} = \frac{K\,A\,(T_{N+1} - T_N)}{L}$$

$$Q_{F \to N} = h\,A_s\,(T_F - T_N)$$

$$\frac{dE}{dt} = \frac{\rho\,V\,C_p\,(T_{1N} - T_N)}{\Delta\,t}$$

Substituting into the energy balance equation and solving for T_{1N} gives

$$T_{1N} = T_N + [C5\,(T_{N+1} + T_{N-1} - 2T_N) + C6\,(T_F - T_N) + C7\,Q_{Gen}]\,\Delta t$$

Where C5 through C7 are known constants depending on material properties, geometry and node spacing, and all quantities on the right side are evaluated at the previous time.

3. Energy balance for the insulated wire nodes

$$Q_{N-1\to N} + Q_{N+1\to N} + Q_{IN\to N} + Q_{Gen} = \frac{dE}{dt}$$

where

$$Q_{N-1\to N} = \frac{K\,A\,(T_{N-1} - T_N)}{L}$$

$$Q_{N+1\to N} = \frac{K\,A\,(T_{N+1} - T_N)}{L}$$

$$Q_{IN\to N} = \frac{K_I\,A_s\,(T_{IN} - T_N)}{L}$$

$$\frac{dE}{dt} = \frac{\rho\,V\,C_p\,(T_{1N} - T_N)}{\Delta t}$$

Substitution and solving for T_{1N} gives

$$T_{1N} = T_N + [C8\,(T_{N+1} + T_{N-1} - 2T_N) + C9\,(T_{IN} - T_N) + C10\,Q_{Gen}]\,\Delta t$$

Where C8 through C10 are known constants and all temperature values on the right side of the above equation are known. Note that T_{1N} is the temperature of the insulated wire node N, Δt seconds after the temperature is equal to T_N.

4. Energy balance for the nodes in the insulation

Energy balance on node "IN"

$$Q_{IN-1 \to IN} + Q_{IN+1 \to IN} + Q_{F \to IN} + Q_{N \to IN} = \frac{dE}{dt}$$

Where

$$Q_{IN-1 \to IN} = \frac{KA\,(T_{IN-1} - T_{IN})}{L}$$

$$Q_{IN+1 \to IN} = \frac{KA\,(T_{IN+1} - T_{IN})}{L}$$

$$Q_{F \to IN} = h\,A_s\,(T_F - T_{IN})$$

$$Q_{N \to IN} = \frac{K\,A_s\,(T_N - T_{IN})}{L}$$

$$\frac{dE}{dt} = \frac{\rho\,V\,C_p\,(T_{1IN} - T_{IN})}{\Delta t}$$

Substituting and solving for T_{1IN} gives

$$T_{1IN} = T_{IN} + [C11\,(T_{IN-1} + T_{IN+1} - 2T_{IN}) + C12\,(T_F - T_{IN}) + C13\,(T_N - T_{IN})]\,\Delta t$$

Where K is the thermal conductivity of the insulation material.

A is the insulation cross section area.
ρ is the density of insulation material.
C_p is the specific heat of insulation material.
V is the volume of insulation material associated with one node.
A_s is the circumferential area.
C11 through C13 are known constants.
T_{1IN} is the temperature of node IN Δt seconds after the temperature = T_{IN}

5. Energy balance for the reference junction nodes

The reference junction (block) is assumed to be the junction between the thermocouple wire and a large mass. It is assumed that the block temperature remains at a constant ambient temperature. It should be noted that connections to pass the required current for the model's LCSR test are made to the bare wire adjacent to the junction so that no I^2R heating occurs in the reference junction.

Energy balance on node "J"

$$Q_{J-1 \to J} + Q_{J+1 \to J} + Q_{Fluid \to J} = \frac{dE}{dT}$$

Where

$$Q_{J-1 \to J} = \frac{KA\,(T_{J-1} - T_J)}{L}$$

$$Q_{J+1 \to J} = \frac{2K_{BL}A_{BL}\,(T_{J+1} - T_J)}{L_{BL}}$$

$$Q_{Fluid \to J} = hA\,(T_F - T_J)$$

$$\frac{dE}{dt} = \rho\, C_p\, V\, \frac{(T_{J1} - T_J)}{\Delta t} \qquad \text{(properties are of block)}$$

The final equation for the reference junction temperature is as follows:

$$T_{J1} = T_J + (C14\,(T_{J-1} - T_J) + C15\,(T_F - T_J) + C16\,(T_{J+1} - T_J))\,\Delta t$$

Where C14 through C15 are known constants. "BL" subscripts are for the block. All other subscripts are listed previously.

11.5 Thermocouple Model Results

To date, the model has been successfully used to predict results for several cases. However, because of the uncertainty in determining the convection heat transfer coefficient "h", it is difficult to match measured results perfectly. Figure 11.5.1 shows actual versus model results for a plunge test of an exposed junction thermocouple. Other examples are provided for the following cases:

1. Typical model plunge tests using different values for the heat transfer coefficient (Figure 11.5.2). This figure is intended to illustrate how differing heat transfer coefficients will affect time constant results. Note all other variables were held constant, and a type "K" thermocouple was used.

2. LCSR transients for a type "K" thermocouple using differing values for "h" (Figure 11.5.3).

3. LCSR transients for a type "K" thermocouple using different wire sizes (Figure 11.5.4). This figure is intended to illustrate how different values for the thermocouple wire diameter will affect the transient response. The wire diameters were 0.25 mm and 0.51 mm.

4. Typical LCSR transients for type E, J, and K thermocouples using constant nominal thermocouple parameters (Figure 11.5.5). Note that the differences in the curves are probably due to different values of thermal conductivity for each of the thermocouples. The transients don't appear to reach final values due to heat transfer along the extension wire.

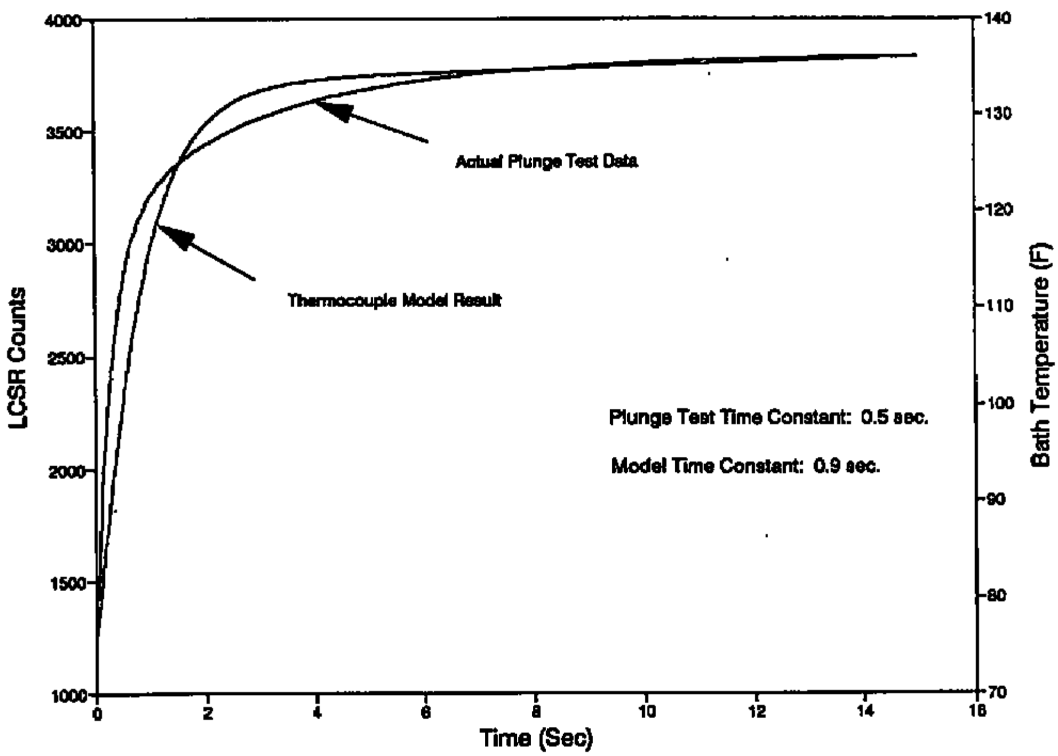


Figure 11.5.1. Model Versus Actual Plunge Test Results.

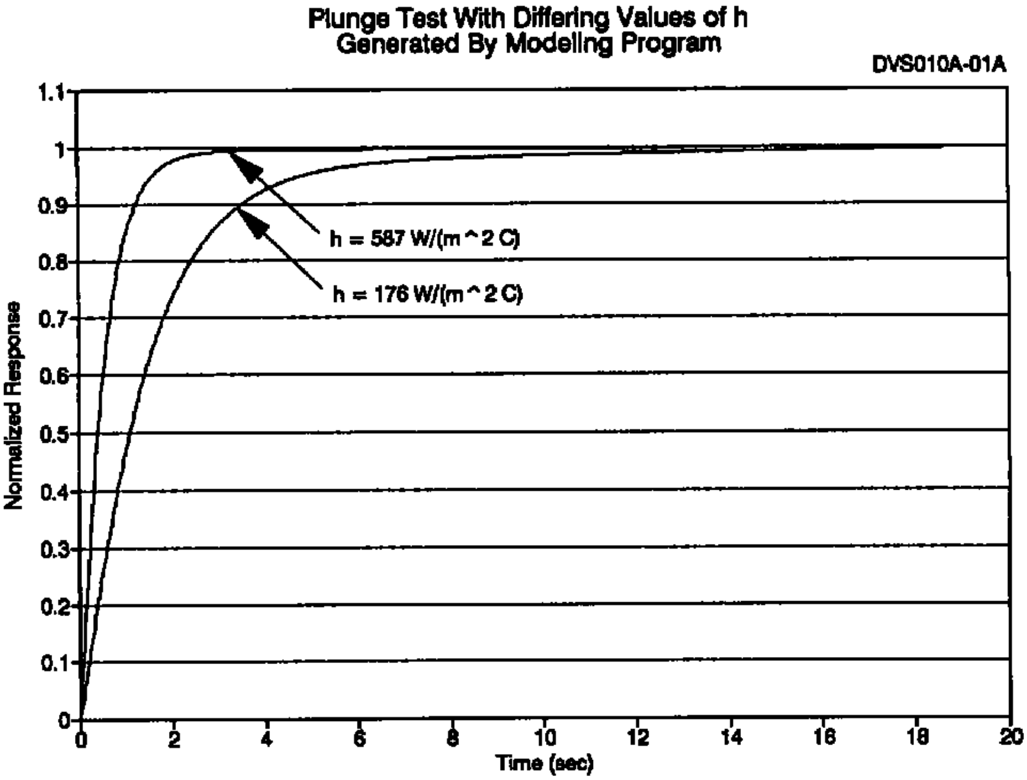


Figure 11.5.2. Model Plunge Test Results Using Different Heat Transfer Coefficients.

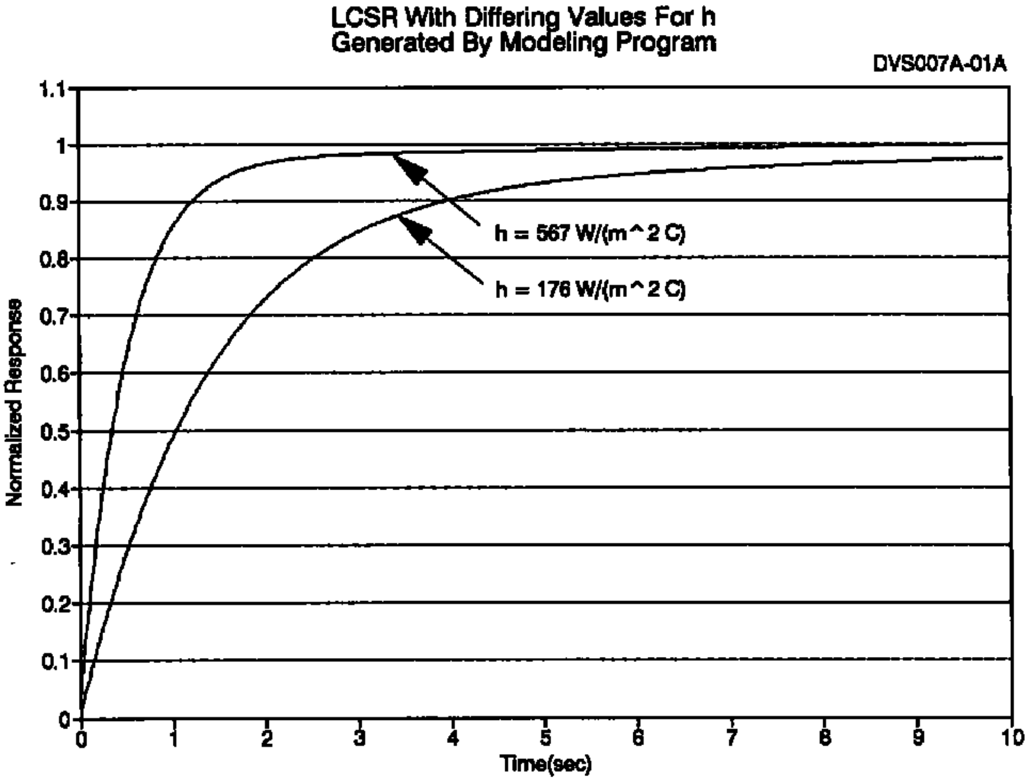


Figure 11.5.3. LCSR Transients for Type "K" Thermocouple Using Different Values of "h".

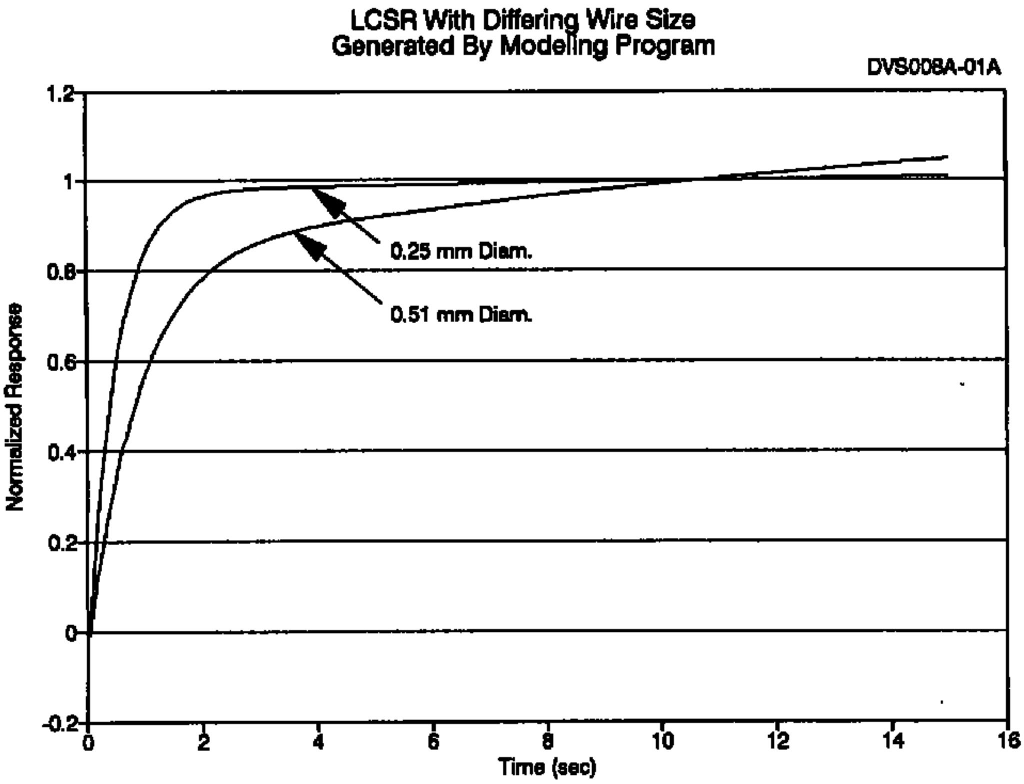


Figure 11.5.4. LCSR Transients for Type "K" Thermocouple Using Different Wire Diameters.

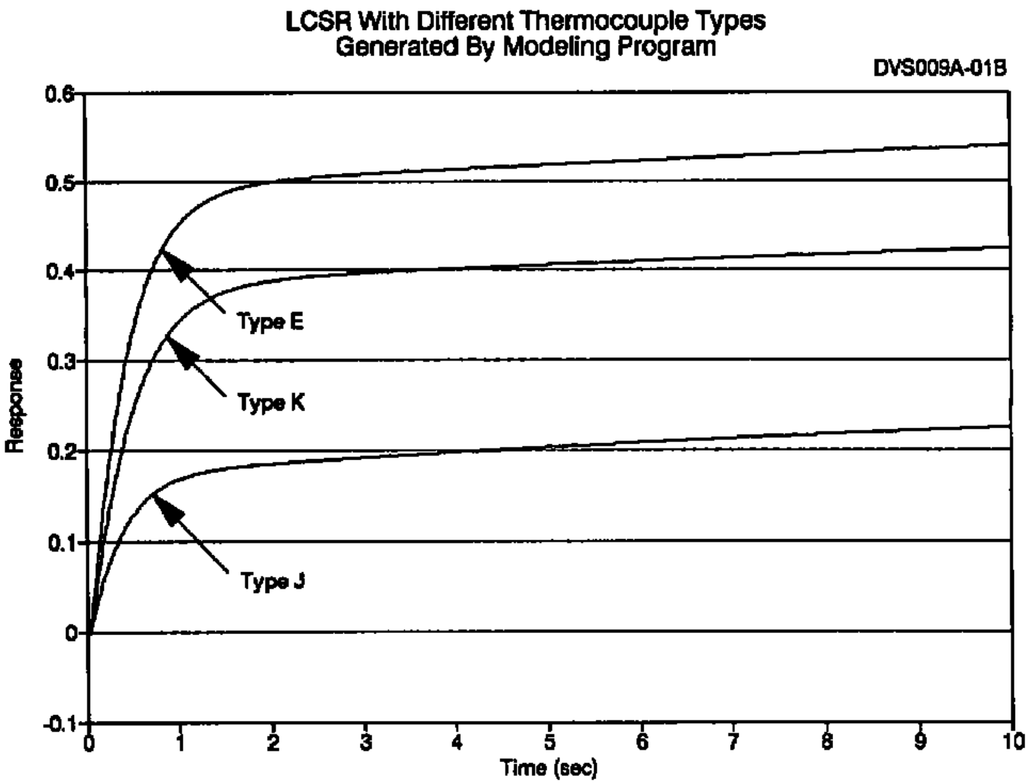


Figure 11.5.5. Typical LCSR Transients for Type "E", "J", and "K" Thermocouples Using the Model.

APPENDIX A

Thermocouple Listing

Thermocouple Characteristics Table (Page 1 of 2)

Tag #	Type	Gage	O.D.(in)	Loop R	Ins. R
AF#1	K Quick	18	1/4	0.61	200 K
AF#2	K Quick	18	1/4	0.53	40 M
AF#3	K Quick GND-JNC	18	1/4	0.45	n/a
AF#4	K Quick	18	1/4	0.65	25 M
AF#5	K Quick	18	1/4	OPEN	>100 G
AF#6	K Quick	20	3/16	0.69	200 K
AF#7	K Quick	20	3/16	0.66	500 M
AF#8	K Trans 36"	20	3/16	2.27	1.5 M
AF#9	K Quick	23	1/8	1.46	10 M
AF#10	K Quick	23	1/8	1.67	15 M
AF#11	K Quick	23	1/8	1.58	1 M
AF#12	K Trans 40" Bent	23	1/8	3.55	n/a
AF#13	K Quick	30	1/16	5.11	4 M
AF#14	K Quick		Flex	1.72	n/a
AF#15	K Quick		Flex		n/a
AF#16	K Quick		Flex	1.2	n/a
AF#17	K Quick		Flex	4.63	n/a
AF#18	K Q-mini EXP-JNC		0.053	113.4	200 K
AF#19	K No CON EXP-JNC		0.053		
AF#20	K Q-mini EXP-JNC		0.052	111.4	150 K
AF#21	K Q-mini GND-JNC		0.053	284	n/a
AF#22	K Q-mini EXP-JNC		0.16	11.6	200 K
AF#23	K Q-mini EXP-JNC		0.16	10.9	350 K
AF#24	K Q-mini GND-JNC		0.052	14	n/a
AF#25	K Q-mini GND-JNC		0.052	13	n/a
AF#26	E Trans 40"	20	3/16	2.87	40 M
AF#27	E Quick	20	3/16	0.79	35 M
AF#28	E Quick	20	3/16	0.77	10 M
AF#29	E Quick	23	1/8	1.57	30 M
AF#30	E Trans 51"	20	1/8	4.38	90 M
AF#31	E Quick	30	1/16	6.15	300 M
AF#32	T Trans 40"	20	3/16	1.62	13 M
AF#33	T Quick GND-JNC	20	3/16	0.47	n/a
AF#34	T Quick	20	3/16	0.41	5 M
AF#35	T Quick	30	1/16	3.07	10 G
AF#36	J Trans 29"	20	3/16	1.47	10 G
AF#37	J Quick	20	3/16	1.03	6.5 M
AF#38	J Quick	24	1/8	1.28	6 M
AF#39	J Trans 51"	20	1/8	2.76	10 M
AF#40	J Quick	30	1/16	3.29	1.2 M

Current as of May 17, 1990

Thermocouple Characteristics Table (Page 2 of 2)

AF#41	E Dual PH assmb.		1/4	0.5	10 G
AF#42	T Dual PH assmb.		1/4	0.45	n/a
AF#43	E Quick	30	1/16	6.9	20 M
AF#44	E Quick	18	1/4	0.85	400 K
AF#45	E Quick	30	1/16	7.2	7 G
AF#46	J Quick	18	1/4	0.6	1.5 M
AF#47	J Quick	30	1/16	3.75	10 G
AF#48	J Quick	30	1/16	4	20 G
AF#49	K Quick	30	1/16	5.8	20 M
AF#50	K Quick	30	1/16	5.8	20 G
AF#51	E Quick EXP-JNC	30	1/16	6.3	4.0 M
AF#52	J Quick EXP-JNC	30	1/16	3.7	1.2 M

Current as of Mav 17. 1990

Calibration Thermocouple Descriptions

Tag #	Description
AFC #01	Type K, 6 mm diameter, SS sheath, standard limits of calibration
AFC #02	Type K, 5 mm diameter, SS sheath, standard limits of calibration
AFC #03	Type K, 3 mm diameter, SS sheath, standard limits of calibration
AFC #04	Type K, 2 mm diameter, SS sheath, standard limits of calibration
AFC #05	Type E, 6 mm diameter, SS sheath, standard limits of calibration
AFC #06	Type E, 5 mm diameter, SS sheath, standard limits of calibration
AFC #07	Type E, 3 mm diameter, SS sheath, standard limits of calibration
AFC #08	Type E, 2 mm diameter, SS sheath, standard limits of calibration
AFC #09	Type J, 6 mm diameter, SS sheath, standard limits of calibration
AFC #10	Type J, 5 mm diameter, SS sheath, standard limits of calibration
AFC #11	Type J, 3 mm diameter, SS sheath, standard limits of calibration
AFC #12	Type J, 2 mm diameter, SS sheath, standard limits of calibration
AFC #13	Type K, 3 mm diameter, SS sheath, cal limits uncertain (shipped as special)
AFC #14	Type J, 3 mm diameter, SS sheath, cal limits uncertain (shipped as special)
AFC #15	Type K, 3 mm diameter, SS sheath, special limits of calibration
AFC #16	Type E, 3 mm diameter, SS sheath, special limits of calibration
AFC #17	Type J, 3 mm diameter, SS sheath, special limits of calibration
AFC #18	Type K, 3 mm diameter, SS sheath, special limits of calibration
AFC #19	Type E, 3 mm diameter, SS sheath, special limits of calibration
AFC #20	Type J, 3 mm diameter, SS sheath, special limits of calibration

APPENDIX B

Thermocouple Modeling Program Source Code

```
' program name is TCMODEL.BAS
'This program analyzes a bare junction thermocouple undergoing an LCSR or plunge test
' curve fit techniques for a first order system are used to get timeconstant
' THE TWO THERMOCOUPLE WIRES ARE IDENTIFIED AS WIRE A AND WIRE B
' I = INSULATION, J = MEASURING JUNCTION, R = REFERENCE JUNCTION
'
'  Modifications:
'
'       8/13/90    If the junction diameter is the same as the wire size,
'                  then the junction is modeled as a cylinder.  Otherwise,
'                  then juction is modeled as a sphere
'

DECLARE SUB PlotTransient (DeviceDriverName$, DeviceName$, X!(), Y!())
DECLARE SUB DefineTestParams ()
DECLARE SUB ErrorMsg (RoutineNum%, IERR%)
DECLARE SUB FormatStringNums (Value$, NumPlaces%)
DECLARE SUB GetKeystroke (KeyVal%)
DECLARE SUB SelectHeatXfer ()
DECLARE SUB SelectModel ()
DECLARE SUB TCDimensions ()
DECLARE SUB WriteModelToFile ()

COMMON SHARED /TCProperties/ KPos!, CpPos!, RhoPos!, KNeg!, CpNeg!, RhoNeg!
COMMON SHARED /TCTypes/ TCType%
COMMON SHARED /TestParams/ NumPts%, DeltaTime!, Filename$, Plunge%
COMMON SHARED /TestParams2/ StartTemp!, BathTemp!, ImmerseLen!, Amperage!
COMMON SHARED /TestParams3/ TimeOfApplication!, KeepHeatUp%, LenInTestArea!
COMMON SHARED /InsulProperties/ KInsul!, CpInsul!, RhoInsul!
COMMON SHARED /Resistivity/ ResPos#, ResNeg#
COMMON SHARED /Dimensions/ WireDiam!, JunctionDiam!, InsulThick!
COMMON SHARED /Lengths/ Area1Len!, Area4Len!, TotalLen!
COMMON SHARED /HeatXfer/ Area1HT!, Area2HT!, Area3HT!, Area4HT!, JunctionHT!
COMMON SHARED /NodeInfo/ NodeSizeArea1!, NodeSizeArea2!, NodeSizeArea3!
COMMON SHARED /NodeInfo2/ NodeSizeArea4!, NodesInArea1%, NodesInArea2%
COMMON SHARED /NodeInfo3/ NodesInArea3%, NodesInArea4%, Area1StartNode%
COMMON SHARED /NodeInfo4/ Area2StartNode%, Area3StartNode%, Area4StartNode%
COMMON SHARED /TimeConst/ TIMECON, TIMEC1

CONST TRUE = -1
CONST FALSE = 0

DIM SHARED TCDims(5) AS STRING * 9
DIM SHARED HeatXfer(5) AS STRING * 7
DIM SHARED Params(6) AS STRING * 6
DIM SHARED Temp$(5)

'
'  Select type of thermocouple to be modeled
'
CALL SelectModel

'
'  Define the dimensions of the thermocouple
'
CALL TCDimensions

'
'  Select heat transfer coefficients for the model
```

```
'
CALL SelectHeatXfer

'
' Define remaining test parameters
'
CALL DefineTestParams

WireRadius! = WireDiam! / 2
JunctionRadius! = JunctionDiam! / 2
NodeSizeArea4! = 10 * WireDiam!
NodeSizeArea1! = WireDiam!
IF Area1Len! / NodeSizeArea1! > 10 THEN
   NodeSizeArea1! = 5 * WireDiam!
END IF

'
' Define Node sizes for regions 2 and 3
'
NodeSizeArea2! = .5
NodeSizeArea3! = 1!

'
' Initialize variables depending on test type
IFLAG1 = 0:  IFLAG2 = 0: ILOOP = 0:   CLS

IF Plunge% THEN
   IFLAG = 0
   Amperage! = 0
   Area2Len! = ImmerseLen! - Area1Len!
ELSE
   IFLAG = 1
   BathTemp! = StartTemp!
   Area2Len! = LenInTestArea! - Area1Len!
END IF

TF1 = StartTemp!
TF4 = StartTemp!
IF Area2Len! < 0 THEN Area2Len! = 0
Area3Len! = TotalLen! - Area4Len! - LenInTestArea!

NodesInArea1% = INT(Area1Len! / NodeSizeArea1!)
NodesInArea2% = INT(Area2Len! / NodeSizeArea2!)
NodesInArea3% = INT(Area3Len! / NodeSizeArea3!)
NodesInArea4% = INT(Area4Len! / NodeSizeArea4!)

Area1StartNode% = 1
Area2StartNode% = NodesInArea1% + 1
Area3StartNode% = NodesInArea1% + NodesInArea2% + 1
Area4StartNode% = NodesInArea1% + NodesInArea2% + NodesInArea3% + 1

READ KBLK, CBLK, RHOBLK, DRJ, LRJ   'REF JNC BLOCK
DATA 30, .15, 600, .75, .5

SampleNum% = 0
RRJ = DRJ / 2
QSA = .1661 * Amperage! ^ 2 * ResPos# / WireRadius! ^ 4
QSB = QSA * ResNeg# / ResPos#
RESJ = (ResPos# + ResNeg#) / 2
REFF = (WireRadius! + JunctionRadius!) / 2
```

```
QSJ = .1661 * Amperage! ^ 2 * RESJ / JunctionRadius! ^ 4
KJ = (KPos! + KNeg!) / 2
CPJ = (CpPos! + CpNeg!) / 2
RHOJ = (RhoPos! + RhoNeg!) / 2
NTOT = NodesInArea1% + NodesInArea2% + NodesInArea3% + NodesInArea4%

REDIM SHARED TA!(NTOT + 1), TB!(NTOT + 1)
REDIM SHARED TIA!(NTOT + 1), TIB!(NTOT + 1)
REDIM SHARED TA1!(NTOT + 1), TB1!(NTOT + 1)
REDIM SHARED TIA1!(NTOT + 1), TIB1!(NTOT + 1)
REDIM SHARED Temps!(NumPts% + 3), Time!(NumPts% + 3)

FOR I = 2 TO NTOT
   TA!(I) = StartTemp!
   TB!(I) = StartTemp!
   TIA!(I) = StartTemp!
   TIB!(I) = StartTemp!
NEXT I
TJ = StartTemp!
TRA = StartTemp!
TRB = StartTemp!
'
'
'
'*******************PARAMETERS FOR EQUATIONS LISTED BELOW*************************************
COA = .04 * KPos! / (RhoPos! * CpPos!)
COB = .04 * KNeg! / (RhoNeg! * CpNeg!)
COI = .04 * KInsul! / (RhoInsul! * CpInsul!)
COBL = .04 * KBLK / (RHOBLK * CBLK * LRJ ^ 2)

CNA1 = .00667 * Area1HT! / (RhoPos! * CpPos! * WireRadius!)
CNB1 = .00667 * Area1HT! / (RhoNeg! * CpNeg! * WireRadius!)
CNA4 = .00667 * Area4HT! / (RhoPos! * CpPos! * WireRadius!)
CNB4 = .00667 * Area4HT! / (RhoNeg! * CpNeg! * WireRadius!)

CWNA = .04 * KInsul! * InsulThick! / ((RhoPos! * CpPos! * WireRadius! ^ 2) * LOG(1 + InsulThick! / (
2 * WireRadius!)))
CWNB = .04 * KInsul! * InsulThick! / ((RhoNeg! * CpNeg! * WireRadius! ^ 2) * LOG(1 + InsulThick! / (
2 * WireRadius!)))

INVC = (25 * RhoInsul! * CpInsul! * (2 * WireRadius! * InsulThick! + InsulThick! ^ 2) * LOG((WireRad
ius! + InsulThick!) / (WireRadius! + InsulThick! / 2)) / (2 * KInsul!))
INVC2 = 300 * RhoInsul! * CpInsul! * (2 * WireRadius! * InsulThick! + InsulThick! ^ 2) / (2 * Area2H
T! * (WireRadius! + InsulThick!))
CON2 = 1 / (INVC + INVC2)
INVC3 = (300 * RhoInsul! * CpInsul! * (2 * WireRadius! * InsulThick! + InsulThick! ^ 2) / (2 * Area3
HT! * (WireRadius! + InsulThick!)))
CON3 = 1 / (INVC + INVC3)
CIN = .08 * KInsul! / (RhoInsul! * CpInsul! * (2 * WireRadius! * InsulThick! + InsulThick! ^ 2) * LO
G(1 + InsulThick! / (2 * WireRadius!)))

RAV = (RhoPos! + RhoNeg!) / 2
CAV = (CpPos! + CpNeg!) / 2

IF ABS((JunctionRadius! - WireRadius!) / WireRadius!) > .01 THEN 'Model as sphere
   CJA = (.06 * KPos! * WireRadius! ^ 2) / (RAV * CAV * NodeSizeArea1! * JunctionRadius! ^ 3)
   CJB = (.06 * KNeg! * WireRadius! ^ 2) / (RAV * CAV * NodeSizeArea1! * JunctionRadius! ^ 3)
   CJN = (.01 * JunctionHT!) / (RAV * CAV * JunctionRadius!)
ELSE   'Model as a cylinder
   CJA = (.08 * KPos!) / (RAV * CAV * NodeSizeArea1! ^ 2)
```

```
   CJB = (.08 * KNeg!) / (RAV * CAV * NodeSizeArea1! ^ 2)
   CJN = ((.01 * JunctionHT!) / (RAV * CAV * JunctionRadius!)) / 3
END IF

CRA = (.04 * KPos! * WireRadius! ^ 2) / (RHOBLK * CBLK * LRJ * RRJ ^ 2)
CRB = (.04 * KNeg! * WireRadius! ^ 2) / (RHOBLK * CBLK * LRJ * RRJ ^ 2)
CWBL = .00333 * Area4HT! * WireRadius! / (RHOBLK * CBLK * LRJ * RRJ ^ 2)

IK = 0: SUM1 = 0: SUM2 = 0: SUM3 = 0: SUM4 = 0: QQK = 1
'
' Coefficients for difference equations
'
C1! = CJA
C2! = CJB
C3! = 1! / (RAV * CAV)
C4! = CJN
C5! = COA / NodeSizeArea1! ^ 2
C6! = 1! / (RhoPos! * CpPos!)
C7! = CWA1
C8! = COB / NodeSizeArea1! ^ 2
C9! = 1! / (RhoNeg! * CpNeg!)
C10! = CWB1
C11! = COA / NodeSizeArea2! ^ 2
C12! = CWNA / Area2Len!
C13! = COB / NodeSizeArea2! ^ 2
C14! = CWNB / Area2Len!
C15! = COI / NodeSizeArea2! ^ 2
C16! = CON2
C17! = CIN
C18! = COA / NodeSizeArea3! ^ 2
C19! = CWNA / Area3Len!
C20! = COB / NodeSizeArea3! ^ 2
C21! = CWNB / Area3Len!
C22! = COI / NodeSizeArea3! ^ 2
C23! = CON3
C24! = COA / NodeSizeArea4! ^ 2
C25! = CWA4
C26! = COB / NodeSizeArea4! ^ 2
C27! = CWB4

TimeConstantFound% = 0   ' False

OPEN Filename$ + ".DAT" FOR OUTPUT AS #1

FOR SampleNum% = 0 TO NumPts%

'  ***********************JUNCTION TEMPERATURE*****************************
   TJ1 = TJ + (C1! * (TA!(2) - TJ) + C2! * (TB!(2) - TJ) + QSJ * C3! + C4! * (BathTemp! - TJ)) * Del
taTime!
   TA1!(2) = TA!(2) + (C5! * (2 * TJ + TA!(3) - 3 * TA!(2)) + QSA * C6! + C7! * (BathTemp! - TA!(2))
) * DeltaTime!
   TB1!(2) = TB!(2) + (C8! * (2 * TJ + TB!(3) - 3 * TB!(2)) + QSB * C9! + C10! * (BathTemp! - TB!(2)
)) * DeltaTime!
   WRITE #1, SampleNum% * DeltaTime!, TJ
   LOCATE 12, 25
   PRINT USING "Calculating Sample #### of ####"; SampleNum%, NumPts%
   LOCATE 13, 14
   PRINT USING "At ###.### sec_, "; SampleNum% * DeltaTime!;
   PRINT USING "the Junction Temperature is ####.## F"; TJ1
'  **************FIRST LOOP-BARE WIRE NEXT TO JNC************************
```

```
   FOR I = 3 TO NodesInArea1%
      TA1!(I) = TA!(I) + (C5! * (TA!(I + 1) + TA!(I - 1) - 2 * TA!(I)) + QSA * C6! + C7! * (BathTemp
! - TA!(I))) * DeltaTime!
      TB1!(I) = TB!(I) + (C8! * (TB!(I + 1) + TB!(I - 1) - 2 * TB!(I)) + QSB * C9! + C10! * (BathTem
p! - TB!(I))) * DeltaTime!
   NEXT I
'  **************SECOND LOOP-INSULATED WIRE INSIDE TEST ENVR*************
   FOR I = Area2StartNode% TO Area3StartNode% - 1
      TIA!(NodesInArea1%) = TIA!(NodesInArea1% + 2)
      TA1!(I) = TA!(I) + (C11! * (TA!(I + 1) + TA!(I - 1) - 2 * TA!(I)) + QSA * C6! + C12! * (TIA!(I
) - TA!(I))) * DeltaTime!
      TB1!(I) = TB!(I) + (C13! * (TB!(I + 1) + TB!(I - 1) - 2 * TB!(I)) + QSB * C9! + C14! * (TIB!(I
) - TB!(I))) * DeltaTime!
      TIA1!(I) = TIA!(I) + (C15! * (TIA!(I + 1) + TIA!(I - 1) - 2 * TIA!(I)) + C16! * (BathTemp! - T
IA!(I)) + C17! * (TA!(I) - TIA!(I))) * DeltaTime!
      TIB1!(I) = TIB!(I) + (C15! * (TIB!(I + 1) + TIB!(I - 1) - 2 * TIB!(I)) + C16! * (BathTemp! - T
IB!(I)) + C17! * (TB!(I) - TIB!(I))) * DeltaTime!
   NEXT I
'  *************THIRD LOOP-INSULATED WIRE OUTSIDE TEST ENVR**************
   FOR I = Area3StartNode% TO Area4StartNode% - 1
      TIA!(Area4StartNode%) = TIA!(Area4StartNode% - 2)
      TA1!(I) = TA!(I) + (C18! * (TA!(I + 1) + TA!(I - 1) - 2 * TA!(I)) + QSA * C6! + C19! * (TIA!(I
) - TA!(I))) * DeltaTime!
      TB1!(I) = TB!(I) + (C20! * (TB!(I + 1) + TB!(I - 1) - 2 * TB!(I)) + QSB * C9! + C21! * (TIB!(I
) - TB!(I))) * DeltaTime!
      TIA1!(I) = TIA!(I) + (C22! * (TIA!(I + 1) + TIA!(I - 1) - 2 * TIA!(I)) + C23! * (TF4 - TIA!(I)
) + C17! * (TA!(I) - TIA!(I))) * DeltaTime!
      TIB1!(I) = TIB!(I) + (C22! * (TIB!(I + 1) + TIB!(I - 1) - 2 * TIB!(I)) + C23! * (TF4 - TIB!(I)
) + C17! * (TB!(I) - TIB!(I))) * DeltaTime!
   NEXT I
'  *********************FOURTH LOOP-BARE WIRE NEXT TO REF JNC************
   KQ = 1
   FOR I = Area4StartNode% TO NTOT
      IF I < (NTOT / 2) THEN GOTO 7000
      KQ = 0  'CURRENT LEADS ATTACHED TO BARE T/C WIRE BETWEEN REF JNC AND INSULATION
7000  TA!(NTOT + 1) = TRA: TB!(NTOT + 1) = TRB
      TA1!(I) = TA!(I) + (C24! * (TA!(I + 1) + TA!(I - 1) - 2 * TA!(I)) + KQ * QSA * C6! + C25! * (T
F4 - TA!(I))) * DeltaTime!
      TB1!(I) = TB!(I) + (C26! * (TB!(I + 1) + TB!(I - 1) - 2 * TB!(I)) + KQ * QSB * C9! + C27! * (T
F4 - TB!(I))) * DeltaTime!
   NEXT I
'
'
'  *********************REFERENCE JUNCTION**********************************
   TRA1 = TRA + (CRA * (TA!(NTOT) - TRA) + (QSA * WireRadius! ^ 2 * NodeSizeArea4!) / (RhoPos! * CpP
os! * RRJ ^ 2 * LRJ) + (COBL + CNBL * Area4Len!) * (TF4 - TRA)) * DeltaTime!
   TRB1 = TRB + (CRB * (TB!(NTOT) - TRB) + (QSB * WireRadius! ^ 2 * NodeSizeArea4!) / (RhoNeg! * CpN
eg! * RRJ ^ 2 * LRJ) + (COBL + CNBL * Area4Len!) * (TF4 - TRB)) * DeltaTime!
'  *************REDEFINE VALUES FOR NEXT LOOP*****************************
   TJBK = TJ:  TJ = TJ1:  TRA = TRA1: TRB = TRB1
   FOR I = 2 TO NTOT
      TA!(I) = TA1!(I): TB!(I) = TB1!(I)
      TIA!(I) = TIA1!(I):  TIB!(I) = TIB1!(I)
   NEXT I

'  **************CLACULATE TIME CONSTANT*************************************
   IF NOT TimeConstantFound% THEN

   IF Plunge% THEN   ' Calculate least squares and .632 time constants
      PAR = ABS((TJ - BathTemp!) / (StartTemp! - BathTemp!))
```

```
        IF PAR <= .8 THEN
          IF IFLAG8 < 10 THEN
            TST = TJ:   PQ = SampleNum%:  IFLAG8 = 10
          END IF
          IF PAR >= .35 THEN
            PAR2 = ABS((TJ - BathTemp!) / (BathTemp! - TST))
            SUM1 = SUM1 + LOG(PAR2)
            SUM2 = SUM2 + DeltaTime! * (SampleNum% - PQ)
            SUM3 = SUM3 + (SampleNum% - PQ) * DeltaTime! * LOG(PAR2)
            SUM4 = SUM4 + ((SampleNum% - PQ) * DeltaTime!) ^ 2
            ++++++++++++++++TIMECON USING .632++++++++++++++++
            IF PAR <= .368 AND IFLAG5 < 3 THEN
              TIMEC1 = SampleNum% * DeltaTime!: IFLAG5 = 5
            END IF
            IK = IK + 1
          ELSE
            TIMECON = ABS((IK * SUM4 - SUM2 ^ 2) / (IK * SUM3 - SUM2 * SUM1))
            TimeConstantFound% = -1   'Set to true
          END IF
        END IF

      ELSE   'It was an LCSR simulation
         IF SampleNum% * DeltaTime! > TimeOfApplication! THEN 'Current is off
           IF IFLAG1 < 4 THEN  ' First step with no current
             QSA = 0: QSB = 0:  QSJ = 0
             TJPK = TJ: ILOOP = 1: IFLAG1 = 6
           END IF

           PAR1 = ABS((TJ - BathTemp!) / (TJPK - BathTemp!))
           IF PAR1 <= .8 THEN
             IF IFLAG9 < 7 THEN  'First point within the window
               TST = TJ: PQ = SampleNum%: IFLAG9 = 15
             END IF
             IF PAR1 >= .2 THEN
               PAR2 = ((TJ - BathTemp!) / (TST - BathTemp!))
               SUM1 = SUM1 + LOG(PAR2)
               SUM2 = SUM2 + DeltaTime! * (SampleNum% - PQ)
               SUM3 = SUM3 + (SampleNum% - PQ) * DeltaTime! * LOG(PAR2)
               SUM4 = SUM4 + ((SampleNum% - PQ) * DeltaTime!) ^ 2
               IK = IK + 1
             ELSE
               TIMECON = ABS((IK * SUM4 - SUM2 ^ 2) / (IK * SUM3 - SUM2 * SUM1))
               TimeConstantFound% = -1  'Set to true
             END IF
           END IF
         END IF
      END IF
      END IF
    NEXT SampleNum%

    CLOSE

    CALL WriteModelToFile

    LOCATE 15, 18
    PRINT USING "Time Constant By Curve Fitting is ###.#### sec"; TIMECON

    IF Plunge% THEN
       LOCATE 16, 15
       PRINT USING "Time Constant at 63.2% of Final Value is ###.#### sec"; TIMEC1
```

```
END IF
IF Plunge% AND PAR > .35 THEN
   LOCATE 17, 15: PRINT "Time Constant not found.  Fitting did not converge"
ELSEIF NOT Plunge% AND PAR1 > .2 THEN
   LOCATE 17, 15: PRINT "Time Constant not found.  Fitting did not converge"
END IF

END

'-----------------------------------------------------------------------
SUB DefineTestParams
'
'  This subroutine asks the user for the remaining info concerning the
'  test.
'
'
'  Get the filename for output
'
Answer$ = ""
ValidFile% = FALSE
LOCATE 2, 17: PRINT "Enter Filename for Output (without extension)"

DO
   LOCATE 3, 36: PRINT SPACE$(30)
   LOCATE 3, 36: INPUT ": ", Answer$
   IF LEN(Answer$) > 0 AND INSTR(Answer$, " ") = 0 THEN
      ValidFile% = TRUE
      IF INSTR(Answer$, ".") <> 0 THEN
         Filename$ = MID$(Answer$, 1, INSTR(Answer$, ".") - 1)
      ELSE
         Filename$ = Answer$
      END IF
   END IF
LOOP UNTIL ValidFile%

'
'  Find out if it is LCSR or Plunge
'
LOCATE 6, 35: PRINT "Type of Test"
LOCATE 7, 36: PRINT "1) LCSR"
LOCATE 8, 36: PRINT "2) Plunge"
LOCATE 9, 36: PRINT "? ";

ValidKey% = FALSE
DO UNTIL ValidKey%
   CALL GetKeystroke(KeyVal%)
   IF KeyVal% = 49 OR KeyVal% = 50 THEN  'A valid key was hit
      Plunge% = 0
      IF KeyVal% = 50 THEN Plunge% = -1
      ValidKey% = TRUE
   END IF
LOOP

'
'  Put up remaining options and initialize them
'
DeltaTime! = .04
NumPts% = 1500
StartTemp! = 120!
BathTemp! = 72!
```

```
ImmerseLen! = 10!
LenInTestArea! = 10!
Amperage! = 1!
TimeOfApplication! = 5!

LOCATE 12, 33: PRINT "Test Conditions"
LOCATE 13, 5: PRINT "Condition": LOCATE 13, 74: PRINT "Value"
LOCATE 14, 5: PRINT "---------": LOCATE 14, 73: PRINT "------"
LOCATE 15, 5: PRINT "Time Interval (sec)"
LOCATE 15, 73: PRINT USING "##.###"; DeltaTime!
LOCATE 16, 5: PRINT "Number of Samples"
LOCATE 16, 73: PRINT USING " #####"; NumPts%
LOCATE 17, 5: PRINT "Start Temperature (F)"
LOCATE 17, 73: PRINT USING " ###.#"; StartTemp!
IF Plunge% THEN
   LOCATE 18, 5: PRINT "Bath Temperature (F)"
   LOCATE 18, 73: PRINT USING " ###.#"; BathTemp!
   LOCATE 19, 5: PRINT "Depth of Immersion (inches)"
   LOCATE 19, 73: PRINT USING " ##.##"; ImmerseLen!
ELSE
   LOCATE 18, 5: PRINT "Amount of Current Applied (amps)"
   LOCATE 18, 73: PRINT USING " ##.##"; Amperage!
   LOCATE 19, 5: PRINT "Time Current is Applied (sec)"
   LOCATE 19, 73: PRINT USING "  ##.#"; TimeOfApplication!
   LOCATE 20, 5: PRINT "Length in Test Area (inches)"
   LOCATE 20, 73: PRINT USING " ##.##"; LenInTestArea!
END IF

'
' Load conditions into strings for editing
'

Tmp$ = LTRIM$(STR$(DeltaTime!))
CALL FormatStringNums(Tmp$, 3)
RSET Params$(1) = Tmp$
Tmp$ = LTRIM$(STR$(NumPts%))
RSET Params$(2) = Tmp$
Tmp$ = LTRIM$(STR$(StartTemp!))
CALL FormatStringNums(Tmp$, 1)
RSET Params$(3) = Tmp$
IF Plunge% THEN
   Tmp$ = LTRIM$(STR$(BathTemp!))
   CALL FormatStringNums(Tmp$, 1)
   RSET Params$(4) = Tmp$
   Tmp$ = LTRIM$(STR$(ImmerseLen!))
   CALL FormatStringNums(Tmp$, 2)
   RSET Params$(5) = Tmp$
ELSE
   Tmp$ = LTRIM$(STR$(Amperage!))
   CALL FormatStringNums(Tmp$, 2)
   RSET Params$(4) = Tmp$
   Tmp$ = LTRIM$(STR$(TimeOfApplication!))
   CALL FormatStringNums(Tmp$, 1)
   RSET Params$(5) = Tmp$
   Tmp$ = LTRIM$(STR$(LenInTestArea!))
   CALL FormatStringNums(Tmp$, 2)
   RSET Params$(6) = Tmp$
END IF
```

```
'  Put up a legend and position to top of list
'
COLOR 1, 7: LOCATE 25, 27: PRINT "  " + CHR$(27) + CHR$(26) + " " + CHR$(24);
PRINT CHR$(25) + SPACE$(10) + "F1= Accept  ";
COLOR 1, 7: LOCATE 15, 73: PRINT Params$(1): COLOR 7, 1
LOCATE 15, 78, 1, 15, 13

IF Plunge% THEN
   MaxDim% = 5
ELSE
   MaxDim% = 6
END IF

DimPtr% = 1
DigitPtr% = 6
KeyVal% = 0
NewVal% = FALSE
NeedDecimal% = TRUE

DO UNTIL KeyVal% = 259    'Until F1 is hit
   CALL GetKeystroke(KeyVal%)

   SELECT CASE KeyVal%
      CASE 272    ' Up arrow was hit
         NeedDecimal% = TRUE
         IF NewVal% THEN
            Params$(DimPtr%) = LTRIM$(TempVal$)
            NewVal% = FALSE
            TempVal$ = "      "
         END IF
         COLOR 7, 1: LOCATE 14 + DimPtr%, 73: PRINT Params$(DimPtr%)
         IF DimPtr% = 1 THEN
            DimPtr% = MaxDim%
         ELSE
            DimPtr% = DimPtr% - 1
         END IF
         DigitPtr% = 6
         COLOR 1, 7: LOCATE 14 + DimPtr%, 73: PRINT Params$(DimPtr%)
         COLOR 7, 1: LOCATE 14 + DimPtr%, 78

      CASE 280    ' Down arrow was hit
         NeedDecimal% = TRUE
         IF NewVal% THEN
            Params$(DimPtr%) = LTRIM$(TempVal$)
            NewVal% = FALSE
            TempVal$ = "      "
         END IF
         COLOR 7, 1: LOCATE 14 + DimPtr%, 73: PRINT Params$(DimPtr%)
         IF DimPtr% = MaxDim% THEN
            DimPtr% = 1
         ELSE
            DimPtr% = DimPtr% + 1
         END IF
         DigitPtr% = 6
         COLOR 1, 7: LOCATE 14 + DimPtr%, 73: PRINT Params$(DimPtr%)
         COLOR 7, 1: LOCATE 14 + DimPtr%, 78

      CASE 275    'Left arrow was hit
         IF NOT NewVal% THEN
            NewVal% = TRUE
```

```
            TempVal$ = "      "
            LOCATE 14 + DimPtr%, 73: PRINT "      ";
            LOCATE 14 + DimPtr%, 73
            DigitPtr% = 1
         END IF
         IF DigitPtr% = 1 THEN
            DigitPtr% = 1
         ELSE
            DigitPtr% = DigitPtr% - 1
         END IF
         LOCATE 14 + DimPtr%, 72 + DigitPtr%

      CASE 277   'Right arrow was hit
         IF NOT NewVal% THEN
            NewVal% = TRUE
            TempVal$ = "      "
            LOCATE 14 + DimPtr%, 73: PRINT "      ";
            LOCATE 14 + DimPtr%, 73
            DigitPtr% = 1
         END IF
         IF DigitPtr% = 6 THEN
            DigitPtr% = 6
         ELSE
            DigitPtr% = DigitPtr% + 1
         END IF
         LOCATE 14 + DimPtr%, 72 + DigitPtr%

      CASE 48 TO 57  'A number was hit
         IF NOT NewVal% THEN
            NewVal% = TRUE
            TempVal$ = "      "
            LOCATE 14 + DimPtr%, 73: PRINT "      ";
            LOCATE 14 + DimPtr%, 73
            DigitPtr% = 1
         END IF
         MID$(TempVal$, DigitPtr%, 1) = CHR$(KeyVal%)
         COLOR 1, 7: LOCATE 14 + DimPtr%, 73: PRINT TempVal$
         COLOR 7, 1
         IF DigitPtr% = 6 THEN
            DigitPtr% = 6
         ELSE
            DigitPtr% = DigitPtr% + 1
         END IF
         LOCATE 14 + DimPtr%, 72 + DigitPtr%

      CASE 46  'Decimal point was hit
         IF NOT NewVal% THEN
            NewVal% = TRUE
            TempVal$ = "      "
            LOCATE 14 + DimPtr%, 73: PRINT "      ";
            LOCATE 14 + DimPtr%, 73
            DigitPtr% = 1
         END IF
         IF NeedDecimal% THEN
            NeedDecimal% = FALSE
            MID$(TempVal$, DigitPtr%, 1) = CHR$(KeyVal%)
            COLOR 1, 7: LOCATE 14 + DimPtr%, 73: PRINT TempVal$
            COLOR 7, 1
            IF DigitPtr% = 6 THEN
               DigitPtr% = 6
```

```
            ELSE
               DigitPtr% = DigitPtr% + 1
            END IF
            LOCATE 14 + DimPtr%, 72 + DigitPtr%
         END IF
   CASE ELSE
      '
      ' Ignore all other keys
      '

   END SELECT
LOOP

'
' Now put the altered numbers back into their proper variables.
'
DeltaTime! = VAL(Params$(1))
NumPts% = VAL(Params$(2))
StartTemp! = VAL(Params$(3))
IF Plunge% THEN
   BathTemp! = VAL(Params$(4))
   ImmerseLen! = VAL(Params$(5))
ELSE
   Amperage! = VAL(Params$(4))
   TimeOfApplication! = VAL(Params$(5))
   LenInTestArea! = VAL(Params$(6))
END IF

CLS

END SUB

'---------------------------------------------------------------------------
SUB ErrorMsg (CallNum%, IERR%)

END SUB

'---------------------------------------------------------------------------
SUB FormatStringNums (Value$, NumPlaces%)
'
' This subroutine will fixed format the number in Value$ to NumPlaces%
' decimal places by filling with extra zeroes.
'
DecLoc% = INSTR(Value$, ".")
IF DecLoc% = 0 THEN
   Value$ = Value$ + "." + STRING$(NumPlaces%, "0")
ELSE
   Value$ = Value$ + STRING$(NumPlaces% - (LEN(Value$) - DecLoc%), "0")
END IF

END SUB

'---------------------------------------------------------------------------
SUB GetKeystroke (KeyVal%)
'
' This subroutine uses the INKEY$ function to get a keystroke from the
' keyboard.  If the key sends an extended code, 200 will be added to
' KeyVal%.  Refer to appendix A.1 of the QuickBASIC Reference Manual for
' a complete list of scan codes.
'
```

```
Answer$ = INKEY$

DO WHILE LEN(Answer$) = 0
   Answer$ = INKEY$
LOOP

IF LEN(Answer$) = 2 THEN
   KeyVal% = ASC(RIGHT$(Answer$, 1)) + 200
ELSE
   KeyVal% = ASC(Answer$)
END IF


END SUB

'---------------------------------------------------------------------------
SUB PlotTransient (DeviceDriverName$, DeviceName$, X!(), Y!())
'
'  This subroutine sets up the axes and labels for a transient plot and
'  generates the transient curve.  Other routines must be called to add
'  transients and end the graph.
'
'  This subroutine requires linking with the GEOGRAF.LIB library in order
'  to use the graphing routines that are called.
'


'
'  Initialization sequence
'
'CALL LoadDriver(DeviceNameDriver$, IERR%)
IF IERR% < 0 THEN
   CALL ErrorMsg(1, IERR%)
   EXIT SUB
END IF

'CALL InitPlot(DeviceName$, 0, IERR%)
IF IERR% < 0 THEN
   CALL ErrorMsg(2, IERR%)
   EXIT SUB
END IF

'CALL StartPlot(0, IERR%)
IF IERR% < 0 THEN
   CALL ErrorMsg(3, IERR%)
   EXIT SUB
END IF

'
'  Set the size of the plotting area big enough to write the labels
'
'CALL setviewport(0, 0!, 0!, 1!, 1!)
'CALL setviewport(0, .15, .0625, .95, .8125)  'creates an 8"x6" plot area
'


END SUB

'---------------------------------------------------------------------------
SUB SelectHeatXfer
'
```

```
'   This subroutine allow the user to define the heat transfer values
'   for the various regions of the thermocouple
'

'
'  Define some of the strings for various areas
'
Junction$ = CHR$(174) + CHR$(175) + CHR$(179)
Area2$ = CHR$(198) + STRING$(14, 205)
Area3$ = CHR$(216) + STRING$(29, 205)
Area4$ = CHR$(181) + STRING$(7, 196)
Block$ = STRING$(6, 177)

'
'  Put up diagram of thermocouple
'
LOCATE 2, 12: PRINT CHR$(179): LOCATE 2, 15: PRINT CHR$(179)
LOCATE 2, 30: PRINT CHR$(179): LOCATE 2, 60: PRINT CHR$(179)
LOCATE 2, 68: PRINT Block$

LOCATE 3, 12: PRINT CHR$(179) + " /" + Area2$ + Area3$ + Area4$ + Block$
LOCATE 3, 70: PRINT CHR$(176) + CHR$(176)

LOCATE 4, 12: PRINT CHR$(179) + CHR$(47): LOCATE 4, 15: PRINT CHR$(179)
LOCATE 4, 30: PRINT CHR$(179): LOCATE 4, 60: PRINT CHR$(179)
LOCATE 4, 68: PRINT Block$

LOCATE 5, 10: PRINT Junction$: LOCATE 5, 15: PRINT CHR$(179)
LOCATE 5, 30: PRINT CHR$(179): LOCATE 5, 60: PRINT CHR$(179)

LOCATE 6, 12: PRINT CHR$(179) + CHR$(92): LOCATE 6, 15: PRINT CHR$(179)
LOCATE 6, 30: PRINT CHR$(179): LOCATE 6, 60: PRINT CHR$(179)
LOCATE 6, 68: PRINT Block$

LOCATE 7, 12: PRINT CHR$(179) + " \" + Area2$ + Area3$ + Area4$ + Block$
LOCATE 7, 70: PRINT CHR$(176) + CHR$(176)

LOCATE 8, 12: PRINT CHR$(179): LOCATE 8, 15: PRINT CHR$(179)
LOCATE 8, 30: PRINT CHR$(179): LOCATE 8, 60: PRINT CHR$(179)
LOCATE 8, 68: PRINT Block$

LOCATE 8, 3: PRINT "Junction": LOCATE 8, 23: PRINT "Area 2"
LOCATE 8, 41: PRINT "Area 3": LOCATE 8, 61: PRINT "Area 4"
LOCATE 9, 11: PRINT "Area 1"
LOCATE 11, 30: PRINT "Heat Transfer Regions"

'
'  Now put up the various heat transfer coefficients along with
'  descriptions of each area
'
LOCATE 12, 5: PRINT "Region": LOCATE 12, 73: PRINT "Value"
LOCATE 13, 5: PRINT "------": LOCATE 13, 72: PRINT "-------"

LOCATE 14, 5: PRINT "Junction      (Region of the weld)"
LOCATE 15, 5: PRINT "Area 1        (exposed wire next to junction)"
LOCATE 16, 5: PRINT "Area 2        (insulated wire inside the test area)"
LOCATE 17, 5: PRINT "Area 3        (insulated wire outside the test area)"
LOCATE 18, 5: PRINT "Area 4        (exposed wire next to reference junction)"

LOCATE 19, 23: PRINT CHR$(201) + STRING$(34, 205) + CHR$(187)
```

```
LOCATE 20, 23: PRINT CHR$(186); TAB(34); "Typical Values"; TAB(58); CHR$(186)
LOCATE 21, 23: PRINT CHR$(186); " Air"; TAB(50); " 1-5    "; CHR$(186)
LOCATE 22, 23
PRINT CHR$(186); " Flowing Air"; TAB(50); " 2-100  "; CHR$(186)
LOCATE 23, 23
PRINT CHR$(186); " Flowing Water"; TAB(50); "20-3000 "; CHR$(186)
LOCATE 24, 23: PRINT CHR$(200) + STRING$(34, 205) + CHR$(188);

'
' Stuff initial values into the various areas and put them on the screen.
'
JunctionHT! = 40
Area1HT! = 40
Area2HT! = 40
Area3HT! = 5
Area4HT! = 5

Temp$(1) = LTRIM$(STR$(JunctionHT!))
Temp$(2) = LTRIM$(STR$(Area1HT!))
Temp$(3) = LTRIM$(STR$(Area2HT!))
Temp$(4) = LTRIM$(STR$(Area3HT!))
Temp$(5) = LTRIM$(STR$(Area4HT!))
FOR I = 1 TO 5
   IF INSTR(Temp$(I), ".") = 0 THEN
      Temp$(I) = Temp$(I) + ".0"
   END IF
   DecLoc% = INSTR(Temp$(I), ".")
   RSET HeatXfer$(I) = MID$(Temp$(I), 1, DecLoc% + 1)
   LOCATE 13 + I, 72: PRINT HeatXfer$(I)
NEXT I

'
' Put up a legend and position to top of list
'
COLOR 1, 7: LOCATE 25, 27: PRINT "  " + CHR$(27) + CHR$(26) + " " + CHR$(24);
PRINT CHR$(25) + SPACE$(10) + "F1= Accept  ";
COLOR 1, 7: LOCATE 14, 72: PRINT HeatXfer$(1): COLOR 7, 1
LOCATE 14, 78, 1, 15, 13

DimPtr% = 1
DigitPtr% = 7
KeyVal% = 0
NewVal% = FALSE
NeedDecimal% = TRUE

DO UNTIL KeyVal% = 259    'Until F1 is hit
   CALL GetKeystroke(KeyVal%)

   SELECT CASE KeyVal%
      CASE 272    ' Up arrow was hit
         NeedDecimal% = TRUE
         IF NewVal% THEN
            HeatXfer$(DimPtr%) = LTRIM$(TempVal$)
            NewVal% = FALSE
            TempVal$ = "       "
         END IF
         COLOR 7, 1: LOCATE 13 + DimPtr%, 72: PRINT HeatXfer$(DimPtr%)
         IF DimPtr% = 1 THEN
            DimPtr% = 5
         ELSE
```

```
      DimPtr% = DimPtr% - 1
   END IF
   DigitPtr% = 7
   COLOR 1, 7: LOCATE 13 + DimPtr%, 72: PRINT HeatXfer$(DimPtr%)
   COLOR 7, 1: LOCATE 13 + DimPtr%, 78

CASE 280   ' Down arrow was hit
   NeedDecimal% = TRUE
   IF NewVal% THEN
      HeatXfer$(DimPtr%) = LTRIM$(TempVal$)
      NewVal% = FALSE
      TempVal$ = "       "
   END IF
   COLOR 7, 1: LOCATE 13 + DimPtr%, 72: PRINT HeatXfer$(DimPtr%)
   IF DimPtr% = 5 THEN
      DimPtr% = 1
   ELSE
      DimPtr% = DimPtr% + 1
   END IF
   DigitPtr% = 7
   COLOR 1, 7: LOCATE 13 + DimPtr%, 72: PRINT HeatXfer$(DimPtr%)
   COLOR 7, 1: LOCATE 13 + DimPtr%, 78

CASE 275   'Left arrow was hit
   IF NOT NewVal% THEN
      NewVal% = TRUE
      TempVal$ = "       "
      LOCATE 13 + DimPtr%, 72: PRINT "       ";
      LOCATE 13 + DimPtr%, 72
      DigitPtr% = 1
   END IF
   IF DigitPtr% = 1 THEN
      DigitPtr% = 1
   ELSE
      DigitPtr% = DigitPtr% - 1
   END IF
   LOCATE 13 + DimPtr%, 71 + DigitPtr%

CASE 277   'Right arrow was hit
   IF NOT NewVal% THEN
      NewVal% = TRUE
      TempVal$ = "       "
      LOCATE 13 + DimPtr%, 72: PRINT "       ";
      LOCATE 13 + DimPtr%, 72
      DigitPtr% = 1
   END IF
   IF DigitPtr% = 7 THEN
      DigitPtr% = 7
   ELSE
      DigitPtr% = DigitPtr% + 1
   END IF
   LOCATE 13 + DimPtr%, 71 + DigitPtr%

CASE 48 TO 57  'A number was hit
   IF NOT NewVal% THEN
      NewVal% = TRUE
      TempVal$ = "       "
      LOCATE 13 + DimPtr%, 72: PRINT "       ";
      LOCATE 13 + DimPtr%, 72
      DigitPtr% = 1
```

```
            END IF
            MID$(TempVal$, DigitPtr%, 1) = CHR$(KeyVal%)
            COLOR 1, 7: LOCATE 13 + DimPtr%, 72: PRINT TempVal$
            COLOR 7, 1
            IF DigitPtr% = 7 THEN
               DigitPtr% = 7
            ELSE
               DigitPtr% = DigitPtr% + 1
            END IF
            LOCATE 13 + DimPtr%, 71 + DigitPtr%

         CASE 46  'Decimal point was hit
            IF NOT NewVal% THEN
               NewVal% = TRUE
               TempVal$ = "       "
               LOCATE 13 + DimPtr%, 72: PRINT "       ";
               LOCATE 13 + DimPtr%, 72
               DigitPtr% = 1
            END IF
            IF NeedDecimal% THEN
               NeedDecimal% = FALSE
               MID$(TempVal$, DigitPtr%, 1) = CHR$(KeyVal%)
               COLOR 1, 7: LOCATE 13 + DimPtr%, 72: PRINT TempVal$
               COLOR 7, 1
               IF DigitPtr% = 7 THEN
                  DigitPtr% = 7
               ELSE
                  DigitPtr% = DigitPtr% + 1
               END IF
               LOCATE 13 + DimPtr%, 71 + DigitPtr%
            END IF
      CASE ELSE
         '
         ' Ignore all other keys
         '

   END SELECT
LOOP

JunctionHT! = VAL(HeatXfer$(1))
Area1HT! = VAL(HeatXfer$(2))
Area2HT! = VAL(HeatXfer$(3))
Area3HT! = VAL(HeatXfer$(4))
Area4HT! = VAL(HeatXfer$(5))

CLS

END SUB

'--------------------------------------------------------------------------
SUB SelectModel
'
' This subroutine allows the user to select the correct set of properties
' for each of the metals used to make up a thermocouple type by selecting
' the desired thermocouple type.  These properties are thermal conductivity
' (K), specific heat (Cp), density (Rho), and resistivity.  Their values
' were extracted from an ASTM table for thermoelement materials.  The units
' used in this program for these properties are listed below and include
' the conversion factors to convert from ASTM units.
'                                                               Conversion
```

```
'    Property       Program Units        ASTM Units            Factor
'    --------       -------------        ----------            ----------
'       K           BTU-ft/hr-ft^2-F        same                  n/a
'      Cp           BTU/lbm-F            cal/g-C                  1.0
'      Rho            lb/ft^3            lb/in^3               1728.0
'    resist           ohm-in              ohm-cm               0.3937
'
'++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
'
'
'  Put up selection menu
'
COLOR 7, 1: CLS

LOCATE 3, 27: PRINT "Select Thermocouple Type"
LOCATE 4, 34: PRINT "1. Type J"
LOCATE 5, 34: PRINT "2. Type K"
LOCATE 6, 34: PRINT "3. Type E"
LOCATE 7, 34: PRINT "4. Type T"
LOCATE 9, 32: PRINT "Enter Choice:";

ValidChoice% = FALSE
DO UNTIL ValidChoice%
   Answer$ = INKEY$
   DO WHILE LEN(Answer$) = 0
      Answer$ = INKEY$
   LOOP
   IF VAL(Answer$) >= 1 AND VAL(Answer$) <= 4 THEN
      LOCATE 9, 46: PRINT Answer$
      ValidChoice% = TRUE
      TCType% = VAL(Answer$)
   ELSE
      LOCATE 11, 20: PRINT "Not a valid selection. Please try again.";
'
'  Now put the altered numbers back into their
      FOR I = 1 TO 10000: NEXT I
      LOCATE 11, 20: PRINT SPACE$(50)
   END IF
LOOP
'
'  For now,  we assume the insulation is the same for all types
'
KInsul! = .15
CpInsul! = .3
RhoInsul! = 80!
InsulThick! = .015625        '1/64 inch

'
'  Get the correct set of properties for the selected thermocouple
'
SELECT CASE Answer$

   CASE "1"     'Type J
      KPos! = 39.2
      CpPos! = .107
      RhoPos! = .284 * 1728!
      ResPos# = 9.670000000000001D-06 * .3937
      KNeg! = 12.2
      CpNeg! = .094
      RhoNeg! = .322 * 1728!
```

```
      ResNeg# = .0000489 * .3937

   CASE "2"     'Type K
      KPos! = 11.1
      CpPos! = .107
      RhoPos! = .315 * 1728!
      ResPos# = .0000706 * .3937
      KNeg! = 17.2
      CpNeg! = .125
      RhoNeg! = .311 * 1728!
      ResNeg# = .0000294 * .3937

   CASE "3"     'Type E
      KPos! = 11.1
      CpPos! = .107
      RhoPos! = .315 * 1728!
      ResPos# = .0000706 * .3937
      KNeg! = 12.2
      CpNeg! = .094
      RhoNeg! = .322 * 1728!
      ResNeg# = .0000489 * .3937

   CASE "4"     'Type T
      KPos! = 218!
      CpPos! = .092
      RhoPos! = .322 * 1728!
      ResPos# = .000001724# * .3937
      KNeg! = 12.2
      CpNeg! = .094
      RhoNeg! = .322 * 1728!
      ResNeg# = .0000489 * .3937

END SELECT


END SUB

'---------------------------------------------------------------------------
SUB TCDimensions
'
' This subroutine allows the user to define the dimensions of the
' thermocouple to be modeled.
'
' Put up the dimension options
'
LOCATE 13, 29: PRINT "Thermocouple Dimensions"
LOCATE 14, 5: PRINT "Dimension": LOCATE 14, 72: PRINT "Value"
LOCATE 15, 5: PRINT "---------": LOCATE 15, 70: PRINT "---------"
LOCATE 16, 5: PRINT "Total Length of Thermocouple Including Extension Wires ";
PRINT "(Inches)"
LOCATE 17, 5: PRINT "Length of Bare Wire Next to Junction (Inches)"
LOCATE 18, 5: PRINT "Length of Bare Wire Next to Reference Junction (Inches)"
LOCATE 19, 5: PRINT "Diameter of Wire Excluding Insulation (Inches)"
LOCATE 20, 5: PRINT "Diameter of Junction (inches)"

'
' Put up the defaults
'
Area1Len! = .03125
Area4Len! = .5
```

```
TotalLen! = 96
WireDiam! = .004
JunctionDiam! = .0125

COLOR 1, 7: LOCATE 16, 70: PRINT USING "###.#####"; TotalLen!: COLOR 7, 1
LOCATE 17, 70: PRINT USING "###.#####"; Area1Len!
LOCATE 18, 70: PRINT USING "###.#####"; Area4Len!
LOCATE 19, 70: PRINT USING "###.#####"; WireDiam!
LOCATE 20, 70: PRINT USING "###.#####"; JunctionDiam!

'
'  Put up a legend and position to top of list
'
COLOR 1, 7: LOCATE 25, 27: PRINT "  " + CHR$(27) + CHR$(26) + " " + CHR$(24);
PRINT CHR$(25) + SPACE$(10) + "F1= Accept  "; : COLOR 7, 1
LOCATE 16, 78, 1, 15, 13   'Position cursor to top of list

'
'  Now let them customize the dimensions
'
ValString$ = LTRIM$(STR$(TotalLen!))
CALL FormatStringNums(ValString$, 5)
RSET TCDims$(1) = ValString$

ValString$ = LTRIM$(STR$(Area1Len!))
CALL FormatStringNums(ValString$, 5)
RSET TCDims$(2) = ValString$

ValString$ = LTRIM$(STR$(Area4Len!))
CALL FormatStringNums(ValString$, 5)
RSET TCDims$(3) = ValString$

ValString$ = LTRIM$(STR$(WireDiam!))
CALL FormatStringNums(ValString$, 5)
RSET TCDims$(4) = ValString$

ValString$ = LTRIM$(STR$(JunctionDiam!))
CALL FormatStringNums(ValString$, 5)
RSET TCDims$(5) = ValString$

DimPtr% = 1
DigitPtr% = 9
KeyVal% = 0
NewVal% = FALSE
NeedDecimal% = TRUE

DO UNTIL KeyVal% = 259    'Until F1 is hit
   CALL GetKeystroke(KeyVal%)

   SELECT CASE KeyVal%
      CASE 272    ' Up arrow was hit
         NeedDecimal% = TRUE
         IF NewVal% THEN
            TCDims$(DimPtr%) = LTRIM$(TempVal$)
            NewVal% = FALSE
            TempVal$ = "         "
         END IF
         COLOR 7, 1: LOCATE 15 + DimPtr%, 70: PRINT TCDims$(DimPtr%)
         IF DimPtr% = 1 THEN
            DimPtr% = 5
```

```
   ELSE
      DimPtr% = DimPtr% - 1
   END IF
   DigitPtr% = 9
   COLOR 1, 7: LOCATE 15 + DimPtr%, 70: PRINT TCDims$(DimPtr%)
   COLOR 7, 1: LOCATE 15 + DimPtr%, 78

CASE 280   ' Down arrow was hit
   NeedDecimal% = TRUE
   IF NewVal% THEN
      TCDims$(DimPtr%) = LTRIM$(TempVal$)
      NewVal% = FALSE
      TempVal$ = "         "
   END IF
   COLOR 7, 1: LOCATE 15 + DimPtr%, 70: PRINT TCDims$(DimPtr%)
   IF DimPtr% = 5 THEN
      DimPtr% = 1
   ELSE
      DimPtr% = DimPtr% + 1
   END IF
   DigitPtr% = 9
   COLOR 1, 7: LOCATE 15 + DimPtr%, 70: PRINT TCDims$(DimPtr%)
   COLOR 7, 1: LOCATE 15 + DimPtr%, 78

CASE 275   'Left arrow was hit
   IF NOT NewVal% THEN
      NewVal% = TRUE
      TempVal$ = "         "
      LOCATE 15 + DimPtr%, 69: PRINT "         ";
      LOCATE 15 + DimPtr%, 69
      DigitPtr% = 1
   END IF
   IF DigitPtr% = 1 THEN
      DigitPtr% = 1
   ELSE
      DigitPtr% = DigitPtr% - 1
   END IF
   LOCATE 15 + DimPtr%, 69 + DigitPtr%

CASE 277   'Right arrow was hit
   IF NOT NewVal% THEN
      NewVal% = TRUE
      TempVal$ = "         "
      LOCATE 15 + DimPtr%, 69: PRINT "         ";
      LOCATE 15 + DimPtr%, 69
      DigitPtr% = 1
   END IF
   IF DigitPtr% = 9 THEN
      DigitPtr% = 9
   ELSE
      DigitPtr% = DigitPtr% + 1
   END IF
   LOCATE 15 + DimPtr%, 69 + DigitPtr%

CASE 48 TO 57  'A number was hit
   IF NOT NewVal% THEN
      NewVal% = TRUE
      TempVal$ = "         "
      LOCATE 15 + DimPtr%, 70: PRINT "         ";
      LOCATE 15 + DimPtr%, 70
```

```
            DigitPtr% = 1
         END IF
         MID$(TempVal$, DigitPtr%, 1) = CHR$(KeyVal%)
         COLOR 1, 7: LOCATE 15 + DimPtr%, 70: PRINT TempVal$
         COLOR 7, 1
         IF DigitPtr% = 9 THEN
            DigitPtr% = 9
         ELSE
            DigitPtr% = DigitPtr% + 1
         END IF
         LOCATE 15 + DimPtr%, 69 + DigitPtr%

      CASE 46  'Decimal point was hit
         IF NOT NewVal% THEN
            NewVal% = TRUE
            TempVal$ = "         "
            LOCATE 15 + DimPtr%, 70: PRINT "         ";
            LOCATE 15 + DimPtr%, 70
            DigitPtr% = 1
         END IF
         IF NeedDecimal% THEN
            NeedDecimal% = FALSE
            MID$(TempVal$, DigitPtr%, 1) = CHR$(KeyVal%)
            COLOR 1, 7: LOCATE 15 + DimPtr%, 70: PRINT TempVal$
            COLOR 7, 1
            IF DigitPtr% = 9 THEN
               DigitPtr% = 9
            ELSE
               DigitPtr% = DigitPtr% + 1
            END IF
            LOCATE 15 + DimPtr%, 69 + DigitPtr%
         END IF
   CASE ELSE
      '
      ' Ignore all other keys
      '

   END SELECT
LOOP

'
' Now put the altered numbers back into their proper variables.
'
TotalLen! = VAL(TCDims$(1))
Area1Len! = VAL(TCDims$(2))
Area4Len! = VAL(TCDims$(3))
WireDiam! = VAL(TCDims$(4))
JunctionDiam! = VAL(TCDims$(5))

CLS

END SUB

'---------------------------------------------------------------------------
SUB WriteModelToFile
'
' This subroutine writes all of the user selected parameters for the data
' to a file that corresponds to to the data file.  Data files have the
' extension .DAT and model files have the extension .MDL
'
```

```
OPEN Filename$ + ".MDL" FOR OUTPUT AS #1

PRINT #1, TAB(15); "This information was used to simulate the";
IF Plunge% THEN
   PRINT #1, " plunge test"
ELSE
   PRINT #1, " LCSR test"
END IF
PRINT #1, TAB(30); "found in "; UCASE$(Filename$); ".DAT"
PRINT #1, : PRINT #1,

IF TCType% = 1 THEN
   Type$ = "J"
   PosMetal$ = "Iron"
   NegMetal$ = "Constantan"
ELSEIF TCType% = 2 THEN
   Type$ = "K"
   PosMetal$ = "Chromel"
   NegMetal$ = "Alumel"
ELSEIF TCType% = 3 THEN
   Type$ = "E"
   PosMetal$ = "Chromel"
   NegMetal$ = "Constantan"
ELSEIF TCType% = 4 THEN
   Type$ = "T"
   PosMetal$ = "Copper"
   NegMetal$ = "Constantan"
END IF
PRINT #1, TAB(30); "Thermocouple Type: "; Type$

PRINT #1, : PRINT #1,
PRINT #1, TAB(25); "Physical Properties of Thermoelements"
PRINT #1,
PRINT #1, " Physical Property"; TAB(25); PosMetal$; TAB(40);
PRINT #1, NegMetal$; TAB(55); "Insulation"
PRINT #1, "-------------------"; TAB(25); STRING$(LEN(PosMetal$), "-");
PRINT #1, TAB(40); STRING$(LEN(NegMetal$), "-"); TAB(55); "----------"
PRINT #1,
PRINT #1, "Thermal Conductivity"; TAB(25);
PRINT #1, USING "###.##         ###.##         ###.##"; KPos!, KNeg!, KInsul!
PRINT #1, "Specific Heat"; TAB(25);
PRINT #1, USING "#.####         #.####         #.####"; CpPos!, CpNeg!, CpInsul!
PRINT #1, "Density"; TAB(25);
PRINT #1, USING "####.#         ####.#         ####.#"; RhoPos!, RhoNeg!, RhoInsul!
PRINT #1, "Resistivity"; TAB(25);
PRINT #1, USING "#.########     #.########      n_/a"; ResPos#, ResNeg#

PRINT #1, : PRINT #1,
PRINT #1, TAB(32); "Configuration Data"
PRINT #1,
PRINT #1, "Description"; TAB(72); "Value"
PRINT #1, "-----------"; TAB(70); "---------"
PRINT #1, "Wire Diameter (inches)"; TAB(70);
PRINT #1, USING " ###.####"; WireDiam!
PRINT #1, "Junction Diameter (inches)"; TAB(70);
PRINT #1, USING " ###.####"; JunctionDiam!
PRINT #1, "Insulation Thickness (inches)"; TAB(70);
PRINT #1, USING " ###.####"; InsulThick!
PRINT #1, "Length of Bare Wire Next to Junction (inches)"; TAB(70);
PRINT #1, USING " ###.####"; AreaILen!
```

```
PRINT #1, "Length of Bare Wire Next to Reference Junction (inches)"; TAB(70);
PRINT #1, USING " ###.####"; Area4Len!
PRINT #1, "Total Length of Thermocouple (inches)"; TAB(70);
PRINT #1, USING "####.## "; TotalLen!
PRINT #1,
PRINT #1, "Heat Transfer Coefficient at Junction"; TAB(70);
PRINT #1, USING "####.## "; JunctionHT!
PRINT #1, "Heat Transfer Coefficient in Area 1"; TAB(70);
PRINT #1, USING "####.## "; Area1HT!
PRINT #1, "Heat Transfer Coefficient in Area 2"; TAB(70);
PRINT #1, USING "####.## "; Area2HT!
PRINT #1, "Heat Transfer Coefficient in Area 3"; TAB(70);
PRINT #1, USING "####.## "; Area3HT!
PRINT #1, "Heat Transfer Coefficient in Area 4"; TAB(70);
PRINT #1, USING "####.## "; Area4HT!
PRINT #1,
IF Plunge% THEN
   PRINT #1, "Initial Temperature (F)"; TAB(70);
   PRINT #1, USING " ###.## "; StartTemp!
   PRINT #1, "Bath Temperature (F)"; TAB(70);
   PRINT #1, USING " ###.## "; BathTemp!
   PRINT #1, "Immersion Length (inches)"; TAB(70);
   PRINT #1, USING " ###.## "; ImmerseLen!
ELSE
   PRINT #1, "Initial (Bath) Temperature (F)"; TAB(70);
   PRINT #1, USING " ###.## "; StartTemp!
   PRINT #1, "Current Applied (Amps)"; TAB(70);
   PRINT #1, USING " ###.## "; Amperage!
   PRINT #1, "Length of Time Current was Applied (sec)"; TAB(70);
   PRINT #1, USING " ###.## "; TimeOfApplication!
   PRINT #1, "Thermocouple Length in Test Area (inches)"; TAB(70);
   PRINT #1, USING " ###.## "; LenInTestArea!
END IF

PRINT #1,
PRINT #1, "Number of Data Points"; TAB(70);
PRINT #1, USING "####     "; NumPts%
PRINT #1, "Time Interval Between Data Points (sec)"; TAB(70);
PRINT #1, USING " ###.## "; DeltaTime!

PRINT #1,
PRINT #1, "Time Constant by Curve Fitting (sec)"; TAB(70);
PRINT #1, USING " ###.####"; TIMECON
IF Plunge% THEN
   PRINT #1, "Time Constant at 63.2% of Final Value (sec)"; TAB(70);
   PRINT #1, USING " ###.####"; TIMEC1
END IF

CLOSE

END SUB
```

APPENDIX C

Aerospace Applications of Thermocouple Response Time

The following report is documentation of a formal survey completed for AEDC to ensure that there is a viable need for LCSR in the aerospace community.

Document # AEDC8901R0

REPORT/PROPOSAL

AEROSPACE APPLICATIONS OF THERMOCOUPLE RESPONSE TIME

June 1989

Prepared for

Arnold Engineering Development Center
Arnold Air Force Base, Tennessee

Project Manager
Mr. Robert W. Smith
U. S. Air Force

SUMMARY

This report presents the results of a technical survey conducted to establish that there is a valid need in the aerospace industry for a capability to measure the response time of thermocouples as installed in operating processes. This survey has provided objective evidence to justify the continuation of a Phase II project being conducted by AMS under the Small Business Innovative Research (SBIR) Program for AEDC. The project is concerned with adaptation of the Loop Current Step Response (LCSR) technique for in-situ measurement of response time of thermocouples in aerospace applications. The project has been approved and work was initiated and continued until November 1988 when the need for this survey was identified. The survey was completed in May 1989 with overwhelmingly positive results. Consequently, AMS is requesting that the project be continued to completion as was originally proposed.

This report also presents a demonstration of work which has been completed at AMS to verify that small current levels can be used to perform the Loop Current Step Response (LCSR) test. This point is addressed in direct response to a recent concern expressed by AEDC with respect to high current levels (up to 5 amps.) that have been used in the past. We have shown that with proper analog and digital signal conditioning, the LCSR test is feasible with current levels of less than 0.5 amps.

TABLE OF CONTENTS

1. INTRODUCTION

Phase I of the SBIR program regarding the determination of installed thermocouple time response has been successfully completed by AMS and the resulting report[1] has been published by AEDC. A follow-on Phase II research program was approved and work was initiated and continued until November of 1988, when AEDC requested a validation of the need for this technology in the aerospace community. The validation has been successfully completed as reported herein.

The validation process involved contacting about 50 technical personnel in the aerospace community. Personnel contacted were from government facilities and the aerospace industry. In addition to telephone responses, a survey package was mailed to all who were contacted. A review of the recent literature in the area of time response of thermocouples has been completed in addition to the survey.

2. TELEPHONE SURVEY

An effort was made to identify the individuals who might have an interest in the time response of thermocouples. We contacted several major aerospace organizations and government laboratories involved in aerospace and instrumentation work. A list compiled for us at AEDC was the best source of knowledgeable people we could find and it was used extensively. Several who were contacted had worked in the technical area several years ago and now hold management positions. All of them were positive about completion of the work, but passed the survey along

to people in their organization who were currently active in related technical areas. Only one individual indicated that he was not interested in seeing the work completed. His reason was that he had not found thermocouples useful in his work which was very high temperature where the thermocouple would melt. Otherwise, the telephone survey was overwhelmingly positive.

3. WRITTEN SURVEY

All individuals contacted by telephone were sent a written survey package to assess whether they believed the LCSR technique was feasible, had promise in aerospace applications, and had any application in their current work. A summary of the response to the various questions along with individual comments is given in Appendix A1. Highlights of the summary include the following:

- 95% of the respondents believe that in-situ measurement of thermocouple time constant offers improved accuracy.
- 95% of the respondents believe that the Air Force needs to be involved with this type of study.
- 65% of the respondents indicated that they knew of a specific application where the LCSR technique might prove valuable.
- 90% of the respondents recommended that the Air Force should complete the program.

Two of the written responses are discussed below in more detail.

Mr. Gus Fralick of NASA-Lewis indicated that "the LCSR technique was rejected in a study by

Pratt & Whitney"[2,3]. Dr. W. S. Johnson, a Professor of Mechanical and Aerospace Engineering and a consultant to AMS, has reviewed the reports in question and has indicated that the objective of the Pratt & Whitney study was to develop a high-temperature, fast response probe, while the LCSR technique is for measurement of the time response of existing thermocouples. His report to AMS is given in Appendix B1. We contacted Mr. Fralick on June 5, 1989 by telephone and discussed the results of our review of his reports. He agreed that there are aerospace applications where LCSR has a good place in spite of the work that has been completed at Pratt & Whitney.

Mr. Brian Bennett of McDonnell-Douglas Aircraft was especially positive regarding the completion of the research project. He indicated that he is currently involved in similar efforts to measure thermocouple response time in-situ for use in the development of a transient enthalpy probe for AEDC. A summary of the enthalpy probe concept and its relation to the LCSR technique is given in Appendix C1.

4. LITERATURE SURVEY

Based on our review of the available technical literature, it is apparent that more future research efforts will be undertaken in the area of thermocouple dynamic response. The ever-present need for better information to allow closer tolerances, higher performance, safety, and quality improvements require more reliable data and tighter specifications, which, in turn depend upon proven, reliable data. A sample of information from literature follows.

- Gray and Thompson[4], state that "There is a clear need for measurement of the time constants of typical thermocouples over a wide range of experimental conditions." They reported success using a technique similar to the LCSR for application of temperature measurement in the ignition of combustible material.

- Johnson and Stainback[5] have measured the rapidly varying temperature of temperature "fronts" in a cryogenic wind tunnel due to the injection of liquid nitrogen. They made use of a hot wire type resistance thermometer for the measurements.

- Ladson and Kilgore[6] discussed instrumentation for calibration and control of a continuous flow wind tunnel and indicated a specific need for a thermocouple with known rapid response time.

- Glawe and Holanda[7] have reported an extensive study to determine thermocouple time constants for gas flows using conventional techniques. They have provided empirical equations to predict time constants in terms of thermocouple size and flow conditions.

- Warshawsky[8] has indicated from results of his work at NASA-Lewis that there are instances in cryogenic engineering where the time constants of thermometers must be known. He has noted that too fast of a response in some cases is dangerous. It is better to use thermometers with moderate response times (but measure the response time and correct from it) than to use a fast thermocouple with a negligible response time. This is because the output of very fast thermocouples is accompanied by extraneous high frequency noise.

The text of the above papers are available at AMS.

5. PERSONAL COMMUNICATIONS

At the 1989 ISA Aerospace Division Symposium held in May, 1989 in Orlando, Florida, an AMS paper entitled, "In-Situ Response Time Testing of Thermocouples"[9] was presented based on the work completed during the program to date. At least 10 persons present at the symposium were personally asked, and all responded positively to the work and the need for its completion. Of particular note were discussions with Dr. Bob Moffat and Dr. Bob Abernethy, both of whom were present for the presentation and were positive about the usefulness of this project and the need

in the aerospace industry. Dr. Moffat indicated that the work should be completed noting that the cost was small compared to the potential benefits. He pointed out that the technique may not work for perforated thermocouples but will work for other types of thermocouples in use in aerospace applications.

6. POTENTIAL AEROSPACE APPLICATIONS

Some specific potential applications of the LCSR technique for aerospace work that we have uncovered are given below:

Jet Engine Testing:

- During engine throttle transients, thermocouples are used to monitor the gas temperature to enable gas properties to be tracked and to determine the condition of the air supplied to cool the turbine blades. Mr. Jerry Wood of Pratt & Whitney Aircraft is currently working on specific techniques to measure the response time of these thermocouples in-situ and feels that the LCSR test has a good potential.

- Several respondents referred to a situation that occurred several years ago involving gas ingestion from fired rocket motors by the engine inlet as an application where the LCSR technology could have been valuable had it been available at the time.

Rocket Engine Testing:

- There is a current test program involving solid rocket motors and there is general agreement that the quality of the available data base is inadequate. Most of the thermocouples of interest are buried in the solid fuel and the time response is not known in-situ. Neither is the quality of the bond between the thermocouple and the solid fuel. The following people specifically mentioned this as an application for the LCSR technique: J. L. Howard of Boeing Aerospace who is currently involved in the project, Steve Lanius of Morton-Thiokol who worked on an earlier phase of the problem and Joe Zimmerman who is the technical monitor for the contract at NASA/MSFC.

Miscellaneous:

- An application that we had not considered previously was suggested by Dr. Peter Dean of Lockheed. They are interested in the quality of the bond between a thermocouple and structural member so that the thermocouple output is indicative of the temperature transient of the member itself when it is exposed to high energy transient flows. Once installed, the thermocouple is buried within the member and not available for inspection. A technique such as LCSR could be used to verify the continuing integrity of the bond. This application also relates to the solid rocket motor testing as described above.

- Several other applications were mentioned by respondents. They include wind tunnel use, verification of mathematical correlations, testing of thin film heat transfer probes, aerodynamic measurements, etc.

REFERENCES

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3. Elmore, D. L., Robinson, W. W., Watkins, W. B., "Further Development of the Dynamic Gas Temperature Measurement System," Vol. I., NASA Report CR179513, August 1986.

4. Gray, P., Thompson, D., "An Experimental Investigation of Thermocouple Response Time in Static Gas Environments," International Journal of Heat and Mass Transfer, Vol. 18, pp. 1207-1211, Pergaman Press, 1975.

5. Johnson, C.B., Stainback, P.C., "Dynamic Measurement of Total Temperature, Pressure, and Velocity - The Langley 0.3 - Meter Transonic Cryogenic Tunnel," NASA Technical Paper 2584, May 1986.

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8. Warshawsky, I., "Heat Conduction Errors and Time Lag in Cryogenic Thermometer Installations," ISA Transactions, Vol. 13, No. 4, pp. 335-346, 1974.

9. Hashemian, H. M., et. al., "In-Situ Response Time Testing of Thermocouples," Proceedings of the 35th International Instrumentation Symposium, Instrument Society of America, Orlando, Florida, May 1989.

APPENDIX A1

Summary of Survey Results

SURVEY RESULTS

Response Time Testing of Thermocouples
(SBIR Phase II Project for AEDC)

June 1, 1989

1. The purpose of the survey was to determine if there is adequate technical interest in the aerospace community to merit completion of the project.

2. The survey was done by mailing a questionnaire to individuals suggested by AEDC and a few other technical individuals in the aerospace community. The questionnaire consisted of ten general questions. The participants were provided with a technical paper about the project and were asked to complete and return the questionnaires to AEDC.

3. Twenty-two people returned the questionnaires (more than 50% of those surveyed responded by returning the questionnaire). The results are summarized in three tables given in the next few pages.

TABLE 1

SURVEY RESULTS

Questions Asked	RESPONSES		
	Positive	Negative	No Response
1. Do you believe that in-situ measurement of thermocouple response times offers improved accuracy over bench tests?	95%	5%	0
2. Do you believe that the Air Force should encourage research efforts in the area of thermocouple dynamic response?	95%	0	5%
3. To what extent do you think that a development such as the LCSR technique can benefit the Air Force and other aerospace activities?	85%	5%	10%
4. Do you have or know of any current or anticipated applications where the LCSR technique might prove valuable? If so, please describe.	65%	35%	0
5. If this project should result in an instrument that can be purchased to perform the LCSR test, do you think that there would be any interest in the aerospace industry?	90%	5%	5%
6. If you anticipate a need for a LCSR instrument, do you have any recommendations on how the instrument may be configured or any special specifications?	N/A	N/A	N/A
7. Based on the information offered herein, do you recommend that AEDC complete the project to develop the LCSR method for aerospace and other applications?	90%	10%	0
8. Is it likely that this capability would find application elsewhere in addition to AEDC?	90%	5%	5%
9. Do you know of any other efforts that have been made to identify the response times of thermocouples in aerospace or other applications?	N/A	N/A	N/A
10. Additional Remarks (if any)	30%	0	70%

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TABLE 2

SUMMARY OF REMARKS

Participant Name	Affiliation	Remarks
G. Fralick	NASA-Lewis	Suggested looking into work done by Pratt & Whitney.
R. Wakefield	NASA-Ames	negative response
B. Henson	NASA-MSFC	"The LCSR method would prove valuable because certain test programs in turbomachinery and engine chambers require temperature measurements of high 'response' characteristics. SRM and SSME NCE examples, both cyrogenic and high temperature ranges." "I don't know about AEDC, but Marshall Space Flight Center would probably have applications for this thermocouple calibration technique."
S. F. Edwards	NASA-Langley	"The LCSR technique can benefit the Air Force and other aerospace activities by more accurate, better prediction of actual thermal measurements." "The LCSR method would prove valuable in aerospace wind tunnel temperature measurements."
K. Daryabeigi	NASA-Langley	"Funding of any viable method of determining in-situ response times of thermometers is recommended." "NASA Langley is interested in this application."
R. Jacobs	AFWAL Wright Patterson	"The LCSR technique can benefit the Air Force and other aerospace activities by rapid, in-service operation and recalibration."
R. McKenzie	NASA-Ames	No significant comments, although answered positively to all questions
J. Zimmerman	NASA-MSFC	"The LCSR technique has the potential for verification of dynamic sensor response for correlation to mathematical predictions." "The LCSR technique could have been valuable to verify proper installation of thermocouples in Solid Rocket Motor Nozzle applications (intimate surface contact)."

continued on next page

Participant Name	Participant Affiliation	Remarks
A. Luper	NASA - WSTF	"Any facility making dynamic temperature measurements, under difficult conditions could use this (technique)."
E. R. Subbarao	Lockheed	"The aerospace community would benefit greatly from the LCSR technique."
		"I foresee the ability for use (of this application) in any thermocouple application."
E. Pauly	General Electric	"The LCSR technique would have been useful in the past during F-18 inlet temperature distortion flight tests to evaluate time response of inlet measurements."
R. Dieck	Pratt & Whitney	"The LCSR technique can benefit the Air Force and other aerospace activities in temperature measurement involving aerodynamic studies."
J. Wood	Pratt & Whitney	"The LCSR technique can benefit the Air Force and other aerospace activities by improvements in low cycle fatigue and transient operation of jet engines."
		"The LCSR technique would prove valuable in transient measurement of turbine blade cooling air and thermal spike measurement of jet engine rocket gas ingestion and rocket engine ignition."
J. L. Howard	Boeing Aerospace	"The testing of solid rocket motor nozzles and materials requires imbedding thermocouples in the composite material matrix to measure temperature. This information is used to determine thermal stress, recession rate and other model parameters. Accurate work requires response time data."
		"I recommend that AEDC complete the project especially if the work can be related to thermocouples imbedded in solid materials (as opposed to being inserted in fluids)."
P. Dean	Lockheed	"The LCSR technique can benefit the Air Force and other aerospace actives by validation of structural thermal response of transient high energy flows."
B. Bennett	McDonnell Douglas	"The LCSR technique would have significant benefit to the Air Force and other aerospace activities."
		"The LCSR technique might prove valuable to the USAF AEDC Transient Enthalpy Probe."

continued on next page

Participant Name	Participant Affiliation	Remarks
M. Langley	Garrett Engine Division	"This (LCSR technique) could be a significant aid in transient testing."
C. Wilkins	EG&G Idaho	"The LCSR technique provides a highly useful technique for data that cannot be reliably obtained by other methods."
D. Pitts	Univ. of Tenn.	"This (thermocouple dynamic response research) is essential to improved experimental work in high speed gas flow." "It would appear that the LCSR technique affords an excellent approach to improvement in accuracy of transient temperature measurement."
A. E. Arave	EG&G Idaho	"Many installations should use this technique (over the bench tests)."
S. Vosen	Sandia Nat'l Labs	"(The LCSR technique) has the capability of increasing the efficiency of experimenters by identifying problems and calibrating without disassembly of experiments." "I think that this method would also be useful in the calibration and testing of thin film heat transfer probes." "I would think that any experiment that has thermocouples imbedded in a large devise, or has an inaccessible thermocouple, would benefit from this method. Even where measurements are being made of steady state temperature, this method could be used to test the operation of the thermocouple."
T. Wang	Thermo Electric Co.	"(This method) would be beneficial for those who need accurate data obtained under actual operating conditions. It would save the expenses in building equipment in the laboratory to simulate actual conditions."

TABLE 3

SURVEY PARTICIPANTS

Government Facilities

	Name	Affiliation	Title
1.	G. Fralick	NASA-Lewis	Engineer
2.	R. Wakefield	NASA-Ames	Asst. Branch Chief, Thermophysics Facilities
3.	B. Henson	NASA-MSFC	Engineer
4.	S. F. Edwards	NASA-Langley	Head, Thermal Inst. Section
5.	K. Daryabeigi	NASA-Langley	Aerospace Technologist
6.	R. Jacobs	Wright Patt.	Electronics Engineer
7.	R. McKenzie	NASA-Ames	Research Scientist
8.	J. Zimmerman	NASA-MSFC	Supervisory Electronic Engineer
9.	A. Luper	NASA-WSTF	Electrical Engineer

Aerospace Industry

10.	E. R. Subbarao	Lockheed	Research Scientist
11.	E. Pauly	GE	Manager, Seperable Instrumentation Engineering
12.	R. Dieck	Pratt & Whitney	Senior Project Engineer
13.	J. Wood	Pratt & Whitney	Engineering Specialist
14.	J. L. Howard	Boeing	Principal Engineer
15.	P. Dean	Lockheed	Research and Development Scientist
16.	B. Bennett	McDonnell Douglas	Senior Engineer
17.	M. Langley	Garrett Engine Division	Sr. Data Validity Engineer

National Labs & Universities

18.	C. Wilkins	EG&G Idaho	Senior Scientist
19.	D. Pitts	Univ. of Tenn.	Professor and Head Mechanical and Aerospace Engineering
20.	A. E. Arave	EG&G Idaho	Engineering Specialist
21.	S. Vosen	Sandia Labs	Technical Staff

Other

22.	T. Wang	Thermo Electric Company	Manager of Thermometry Research

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APPENDIX B1

Evaluation of Pratt & Whitney Report on Thermocouples for NASA-Lewis

THE UNIVERSITY OF TENNESSEE
KNOXVILLE

College of Engineering
Mechanical and Aerospace Engineering

May 26, 1989

TO: H. M. Hashemian

FROM: Dr. W. S. Johnson
Professor of Mechanical Engineering

SUBJECT: Review of NASA CR-168267 and NASA CR-179513 with specific attention to how they relate to the LCSR technique as proposed by AMS.

Per your request, I have reviewed the above reports. It is my understanding that Mr. Fralic of NASA thought that this work had evaluated and rejected the LCSR technique. This is not the case at all, and my conclusions are briefly summarized below:

The objective of the above reports was to develop a new high-temperature, fast response temperature measurement system. This is completely different from the objective of the application of the LCSR technique which is to evaluate the time response of existing temperature probes for all ranges of temperature and time response.

In the NASA work, an effort was made to measure the time response of a thermocouple using a pulsed loop current to produce a periodic temperature-time function having an amplitude of 500 K and frequencies up to 1000 Hz. Difficulties arose in the feedback control circuit which was required to maintain the desired temperature amplitude and in the switching circuit which was needed to produce the high frequency of pulses. The pulse technique was rejected due to the difficulties of circuitry mentioned above. It is noted that the LCSR technique does not use a pulsing technique and uses a single step of low temperature amplitude so that these criticisms do not extend to the LCSR technique.

In summary, no evidence is presented in these reports that would allow one to reject the LCSR technique for the measurement of time response of existing temperature probes.

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APPENDIX C1

Review of Information About Enthalpy Probe

May 31,1989

TO: H. M. Hashemian

FROM: Stan Johnson

SUBJECT: Review of the "Enthalpy Probe report", AEDC-TR-88-1

The enthalpy probe has been developed to measure the enthalpy of high temperature plasmas by a method whereby total pressure and mass flow rate are the only quantities to be directly measured and the resulting enthalpy is calculated from these values. Enthalpy is frequently as important and sometimes more important to know as is temperature. Of course, if accurate specific heat values are known, one may be determined from the other.

The probe operates by pulling a sample through a flow channel where it is cooled and it's mass flow determined by pressure and temperature measurements, which are used along with the total pressure measurement at the probe inlet to determine enthalpy. The probe is swept across the flow channel (rate unspecified) so that all measurements are made under transient conditions, although the basic equations utilized are steady state. This necessitates a time compensation between measurements made at the inlet and exit of the probe to eliminate the time delay effect.

The sonic nozzle concept is a good one because flow rate can be determined in terms of only pressure and temperature. After the stream is passed through a heat exchanger and cooled down to below 500 F, a thermocouple is used to measure the temperature and a standard transducer is used for pressure measurement.

Of particular interest to us is the method of determining the time constant of the thermocouple. The technique used both empirical equations and a modified LCSR experimental technique. Although the details are quite sketchy, the procedure involved heating the thermocouple junction with a power supply, then switching to the data recording circuit and simultaneously switching on the flow. They did not do this procedure under actual operating conditions because the time available was too short and conditions were unsteady. Tests were done with the thermocouple mounted inside the probe, however. They have reported good agreement between this technique and the empirical information to determine time constants. Using this information regarding time constant, they managed to compensate the probe for the time delay between measurements at the probe inlet and exit.

There is significant uncertainty regarding the accuracy of this probe due to considerable fluctuations of the plasma flow when efforts to calibrate the results were attempted. Also, there is no standard measurement probe currently available. About all they could do was to state that results were reasonable based on some overall projections.

APPENDIX D

Field Testing of the LCSR Technique for Thermocouples

Enclosed in this Appendix is a report sent to the Lockheed Aeronautical Systems Company concerning laboratory and field tests of thermocouples for the Solid Propulsion Integrity Program. The information enclosed herein is a typical example of an application for thermocouple LCSR.

ANALYSIS AND
MEASUREMENT SERVICES
CORPORATION

9111 CROSS PARK DRIVE NW / KNOXVILLE, TN 37923-4599 / (615) 691-1756

Report No. LAC9001R0

To: Dr. Peter Dean
Lockheed Aeronautical Systems Company

From: Kent M. Petersen

Date: February 20, 1990

Subject: Laboratory and Field Tests of Thermocouples for Solid Propulsion Integrity Program

INTRODUCTION

Analysis and Measurement Services Corporation (AMS) performed response time tests on several thermocouples for Lockheed Aeronautical Systems Company. These tests were performed for a program called "Solid Propulsion Integrity" sponsored by NASA. The work described in this report pertains to the use of thermocouples for transient temperature measurements made inside the nozzle materials used in solid fuel rocket engines. The purpose of these tests was to demonstrate the usefulness of the Loop Current Step Response (LCSR) method for in-situ measurements of thermocouple response time. More specifically, Lockheed is interested in using the LCSR method as a means of checking the installation integrity of thermocouples when used in solid material before and after high temperature tests of the material. Furthermore, Lockheed is interested in response time estimates for the thermocouples while the test of the solid material is in progress.

DESCRIPTION OF WORK

Two series of tests were performed. The first tests were performed at AMS with two thermocouples provided by Lockheed. These tests were performed to establish the capability of the LCSR method for measuring the response time of thermocouples installed in the nozzle material. The second series of tests were performed at the "Arc Jet Facility" of NASA's Marshall Space Flight Center in Huntsville, Alabama. At this facility, the solid material is exposed to a high temperature using an Arc Jet facility. The purpose of the tests reported herein was to verify whether or not the thermocouples remain in place and intact during the firing process and to obtain an estimate for the response times of the thermocouples during firing. This was accomplished by making response time measurements on these thermocouples before and after firing.

The results successfully demonstrated the capability of the LCSR method to provide useful information about the installed response characteristics of the thermocouples tested.

DESCRIPTION OF THE LCSR METHOD

The LCSR method involves supplying an electric current through the thermocouple leads. The current heats the thermocouple to an elevated temperature several degrees above the ambient temperature. The heating current is then stopped and the output from the thermocouple is monitored as it cools back to the ambient temperature. This cooling transient is then analyzed to

identify the time constant of the thermocouple. The validity of the LCSR method for in-situ response time testing of installed thermocouples has been established by AMS under a project for the U.S. Air Force sponsored by Arnold Engineering Development Center (AEDC).

LABORATORY TESTS AT AMS

Laboratory tests were performed on two type K grounded junction thermocouples provided by Lockheed. Both thermocouples had a sheath diameter of 0.020 inches and were made of 37 gage thermocouple wire. Lockheed also provided a test fixture of "Carbon Phenolic" material approximately 3/4" x 3/4" x 2 3/4" as shown in Figure 1. This block is a section of a larger piece which had previously been exposed to a high temperature on one surface (indicated by "Fired Surface" in Figure 1). This high temperature exposure resulted in two distinct areas of material separated by a transition zone. Two holes had been drilled in the test block - one in each of these distinct areas. Hole #1 is located in the portion of the block away from the fired end of the block. Hole #2 is located near the fired surface of the block in the area of the block that was affected by the elevated temperatures. It was also noted that hole #2 seemed rougher than hole #1 upon insertion of the thermocouples. The two thermocouples were each tested in both of these two holes.

The two thermocouples were tagged LC#1 and LC#2. The first test performed on the thermocouples was a plunge test. The plunge test is a direct measurement of the response time of a sensor under known conditions. In this test, the two

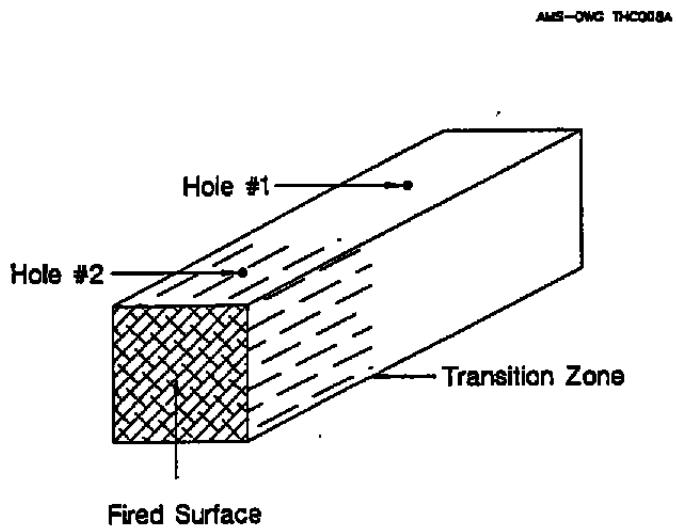

Figure 1. Carbon Phenolic Test Fixture For Laboratory Tests.

thermocouples were first heated above room temperature and then inserted into room temperature air flowing at approximately 3600 fpm transverse to the sensor. The sensor time constant was determined by evaluating the time for the response to cover 63.2 percent of the total span. Figure 2 shows typical plunge test transients for both thermocouples tested. The purpose of this test was to establish the relative intrinsic response times of the two thermocouples. Table 1 shows the results of this test.

Table 1. Plunge Test Results at Room Temperature Air Flowing at 3600 fpm.

Item	Tag #	Time Constant (sec)
1	LC#1	0.6
2	LC#2	0.6

Next, the thermocouples were response time tested in each of the two holes in the test fixture using the LCSR method. Tests were performed with the thermocouples fully inserted in the holes as well as withdrawn approximately halfway from the bottom of the hole to see how changes in installation affect response time. Table 2 lists the results of these tests.

Table 2. Laboratory LCSR Test Results

	Time Constant (sec)		
Tag #	Hole #1	Hole #2	Configuration
LC#1	14	2	Fully Inserted
	11	9	Withdrawn Halfway
LC#2	11	1	Fully Inserted
	11	3	Withdrawn Halfway

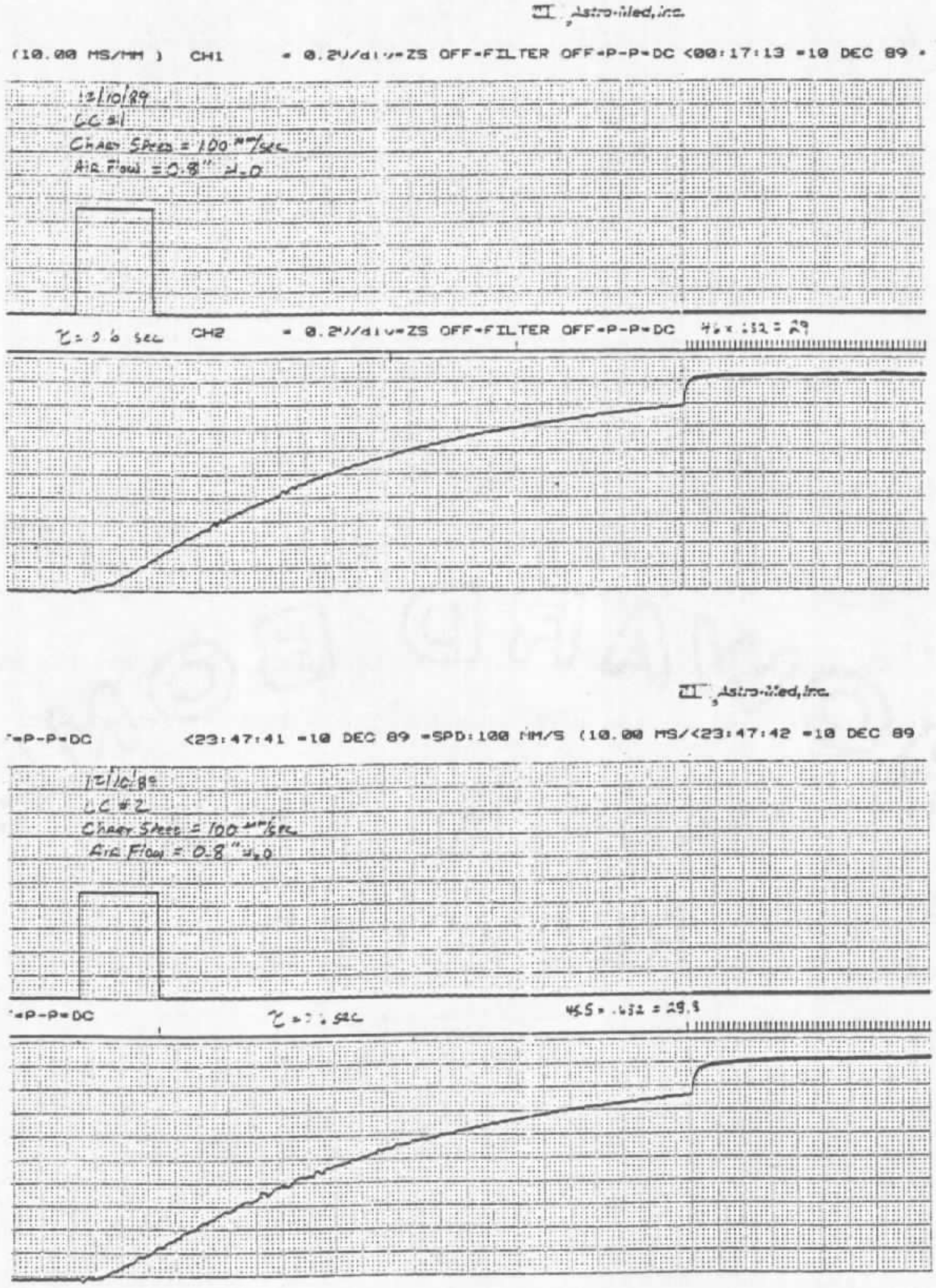

Figure 2. Typical Plunge Test Transients
For LC#1 (above) and LC#2 (below).

The results indicate that:

1. Both thermocouples are faster in hole #2. Hole #2 is the one with a rough surface in which we expected the thermocouples to have better response times.

2. The response time changes with insertion depth only in hole #2. This does not happen in hole #1 because the heat transfer in hole #1 is obviously so poor that it does not make much difference how deep the thermocouple is inserted.

3. Hole #2 is probably in a region of better heat transfer. That is, the Carbon Phenolic material may have lost some of its insulation properties after it was fired upon.

Figure 3 shows typical LCSR transients from tests in hole #1 where there was no significant effect due to insertion depth. Note that the two transients decay at approximately the same rate. Figure 4 shows similar data from tests in hole #2. The large difference between the decay rates of the LCSR transients is apparent in this figure.

Next we added a thermal coupling material called NEVER-SEEZ to hole #2 prior to inserting thermocouple LC#2. The purpose of this test was to demonstrate response time improvements when heat transfer is improved in the hole. Never-Seez has excellent heat transfer characteristics (at temperatures below 300°C) and is sometimes used for response time improvements in thermowells of temperature sensors. The results of tests with Never-Seez (NS) are shown in Table 3. The addition of Never-Seez did not affect the response time of the thermocouple while fully inserted in hole #2. This result helped verify that optimum contact between the thermocouple and the bottom of hole #2 was obtained during the tests without Never-Seez. There was an improvement in the response time at the halfway withdrawn point as expected.

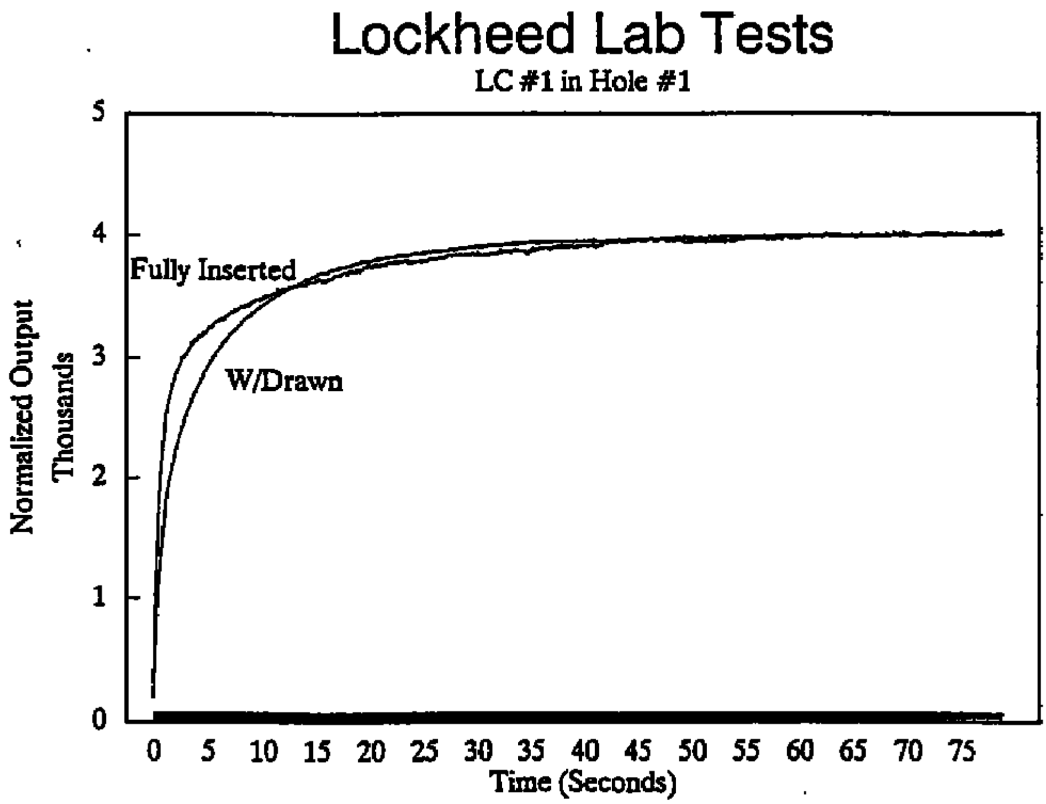

Figure 3. LCSR Transients For LC#1 Installed in Hole #1.

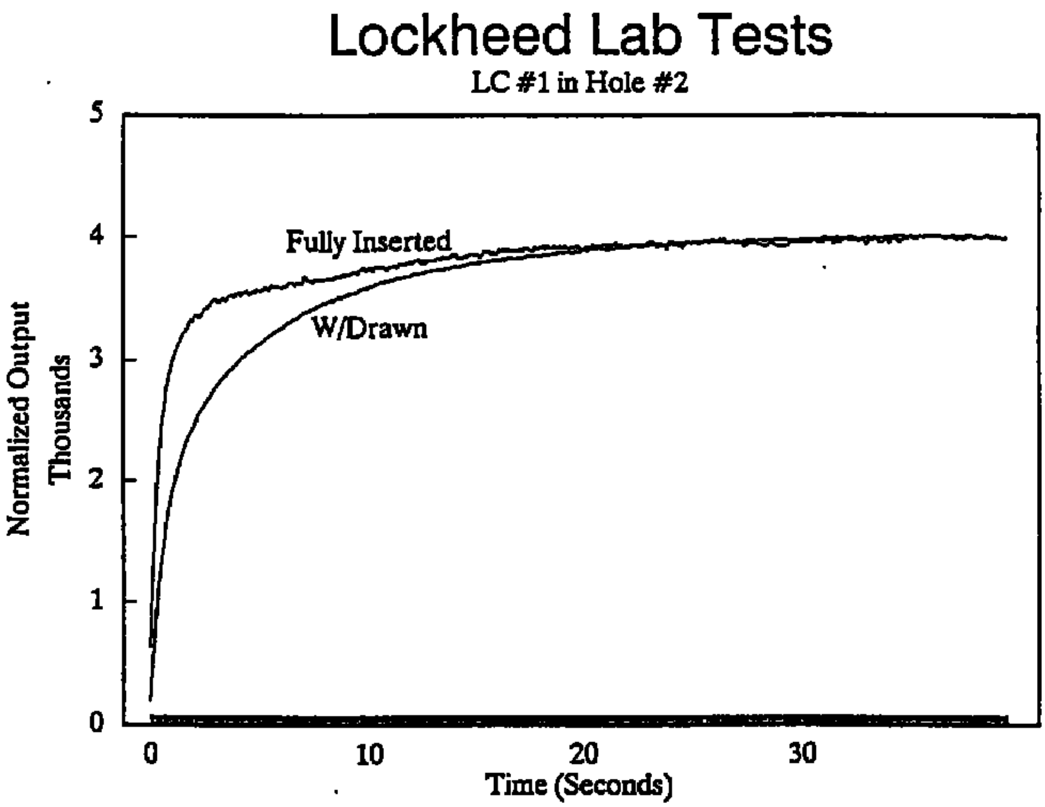

Figure 4. LCSR Transients For LC#1 Installed in Hole #2.

The tests performed in the laboratory demonstrate that the LCSR results are a good indication of installation quality of the thermocouples and the heat transfer characteristics of the material in contact with the thermocouple.

Table 3. Response Times in Test Fixture With and Without Never Seez (Tag # LC #2 in Hole #2)

Configuration	Time Constant (sec) W/O NS	Time Constant (sec) W/NS
Fully Inserted	1.0	1.0
Withdrawn Halfway	3.0	0.6

Tests at Marshall Space Flight Center

On December 12 and 13, 1989, Lockheed performed a series of tests at the Arc Jet facility of Marshall Space Flight Center. One of the five tests performed involved placing four thermocouples and a fiber optic "light pipe" based temperature sensor in a carbon phenolic test block. The block was then exposed to the high temperature of the Arc Jet while temperature data was acquired from the five temperature sensors. AMS performed response time tests on the five thermocouples before and after firing the Arc Jet. These tests had two purposes. First to compare the relative response times of the four thermocouples and second to identify any change in the thermocouple response times as a result of the firing tests. Figure 5 shows the 2" x 2" x 1" carbon phenolic material in which the thermocouples and fiber optic sensors were installed. Table 4 summarizes the characteristics of the thermocouples which were used in this test.

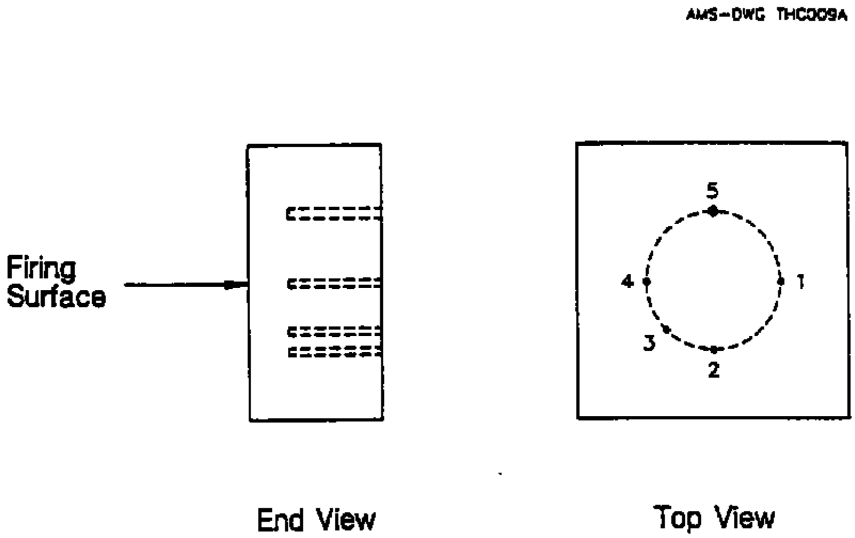

Figure 5. Carbon Phenolic Test Block For Tests Performed at Marshall Space Center.

The four thermocouples were installed dry (without any thermal couplant) into their respective locations in the test block. AMS then performed response time tests on the thermocouples using the LCSR method. The tests were performed on the bench prior to placing the test block in the Arc Jet assembly.

Table 4. Thermocouples Used for Marshall Space Flight Center Tests

Item	Tag #	Junction Type	Sheath Dia. (Inches)	Wire Size (Gage)	Location Per Figure 5
1	MSF #1	Grounded	0.0200	37	1
2	MSF #2	Grounded	0.0625	30	2
3	MSF #3	Insulated	0.0200	37	3
4	MSF #4	Exposed	0.0200	37	4

Note: The light pipe thermometer was installed in location #5.

The test block with the thermocouples was then placed in the Arc Jet test assembly and was subjected to several temperature transients. Transient temperature data from the four thermocouples and the light pipe was acquired by Lockheed personnel during these tests. Problems were encountered during the firing tests with the signals from the two grounded junction thermocouples (MSF #1 and MSF #2). The problem appeared to have been related to electrical contact between the grounded junction thermocouples and the test block as well as between the test block and the clamp assembly which held the block in front of the Arc Jet. These problems did not affect the LCSR tests since the LCSR tests were performed on the bench without grounding the block into which the thermocouples were installed. The fact that the exposed junction thermocouple (MSF #4) did not exhibit any problem during the firing tests indicates that the

measuring junction of the thermocouple was not in contact with the inside surface of the test block.

After the firing tests were completed, the block cooled and removed from the Arc Jet assembly, AMS repeated the LCSR tests on the four thermocouples. Table 5 compares the results of the pre and post-firing response time tests.

Table 5. Pre- and Post-Firing LCSR Results

Item	Tag #	Time Constant (sec) Pre-Firing	Time Constant (sec) Post-Firing
1	MSF #1	13	15
2	MSF #2	23	18
3	MSF #3	30	26
4	MSF #4	31	23

With the exception of MSF #4, the exposed junction thermocouple, the test results indicate that there were no significant changes in the response times of the thermocouples as a result of the firing tests. The small differences in the results are due to repeatability of the LCSR test and slight changes in thermocouple installation before and after firing.

The exposed junction thermocouple (MSF #4) may have been shifted in position in the test block between the pre and post-firing tests. Figures 6 and 7 show typical LCSR transients for both pre and post-firing conditions for two of the four thermocouples. This includes LCSR data for thermocouple #1 which did not experience a change, and thermocouple #4 which did experience a change.

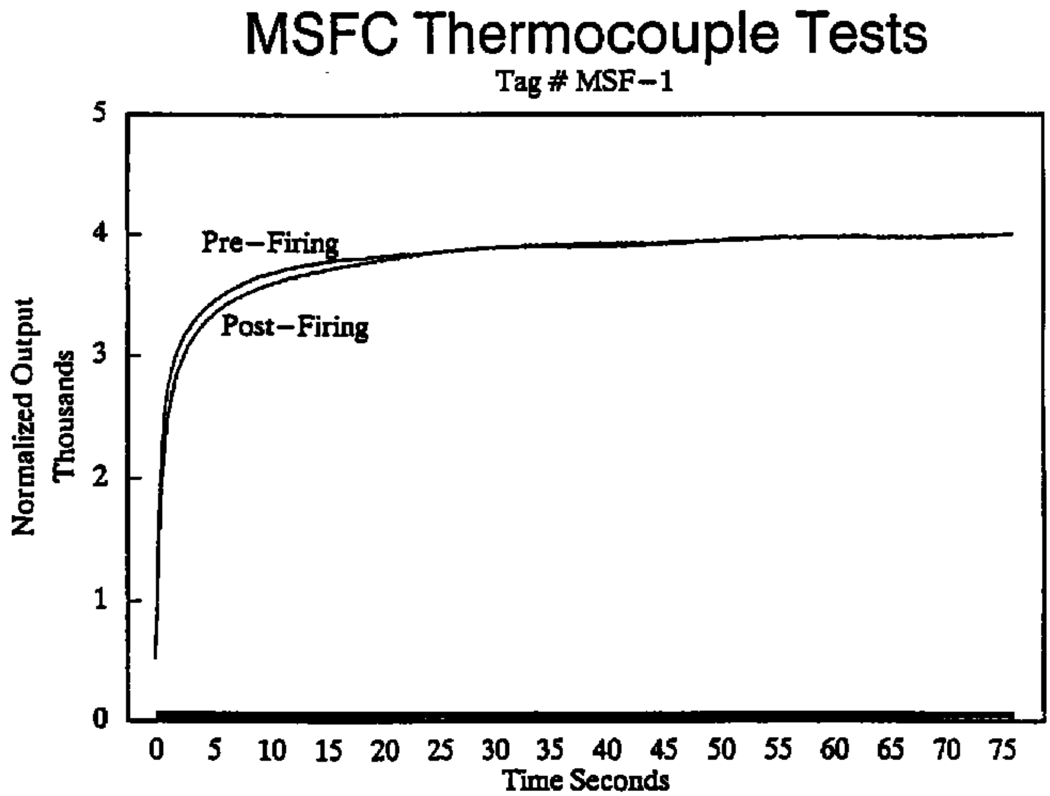

Figure 6. Pre and Post-Firing LCSR Transients For MSF #1.

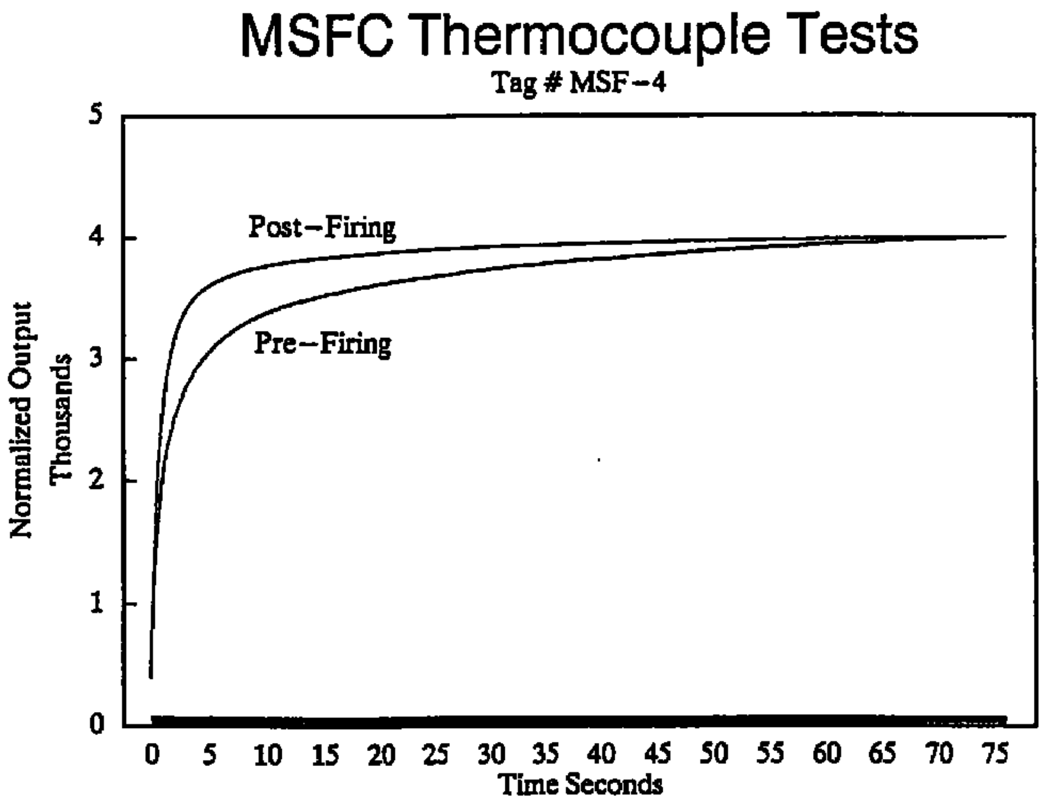

Figure 7. Pre and Post-Firing LCSR Transients For MSF #4.

Response Time Results During Firing

AMS utilized a simple theoretical model of a typical thermocouple to estimate the response times during firing conditions of the four thermocouples used at Marshall. The approach was to establish the model parameters based on the average of the pre and post-firing LCSR results. The effect of the elevated temperatures during the firing test was then applied to the material properties used in the model to estimate the response times under firing conditions. For the exposed junction thermocouple (MSF #4), an additional adjustment was made to the model to account for radiation heat transfer between the junction and the inside wall of the test block. The estimated response times from the modeling effort are given in Table 6.

Table 6. Response Times of Thermocouples at Firing Conditions

Item	Tag #	Time Constant (sec)
1	MSF #1	11
2	MSF #2	21
3	MSF #3	28
4	MSF #4	11

SUMMARY

Table 7 summarizes the results of the tests performed at Marshall as well as the modeling results. The conclusion is that except for thermocouple #4, there was no major changes in response times of the thermocouples due to firing.

The response time estimates during firing did not show large response time improvements. This is because the response time of thermocouples in well-mounted installations such as the one used here is predominately affected by the heat transfer between the thermocouple measuring junction and the wall of the well. Therefore, the improvements in heat transfer at high temperatures in thermocouples and its surrounding materials are not large enough to show significant response time improvements.

Table 7. Summary

		Time Constant (sec)		
Item	Tag #	Pre-Firing	During Firing	Post Firing
1	MSF#1	13	11	15
2	MSF#2	23	21	18
3	MSF#3	30	28	26
4	MSF#4	31	11	23

GENERAL CONCLUSIONS

Our general conclusion regarding the use of the LCSR method is that the method is useful to Lockheed in the following areas:

1) To measure the relative response time of different types of thermocouples installed in the nozzle material.

2) To verify that thermocouples are properly installed for optimum dynamic performance.

3) To determine whether or not the firing or other tests can change the bonding of the thermocouples with the materials in which they are imbedded.

4) To identify changes in heat transfer properties of the materials that are in contact with thermocouples.

5) To provide baseline data required to estimate the thermocouple response times at firing or other process conditions.